Direct Steam Generation (DSG)

Technology Overview

SFERA Summer School 2012
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(Jan) Fabian Feldhoff

DLR

STE Status

- Many market players
- Need for significant cost reduction
    - More automated production and construction
    - Optimized collector designs
    - New heat transfer fluids
        - Direct Steam Generation (DSG)
        - Molten Salt
    - …

→ Today: DSG

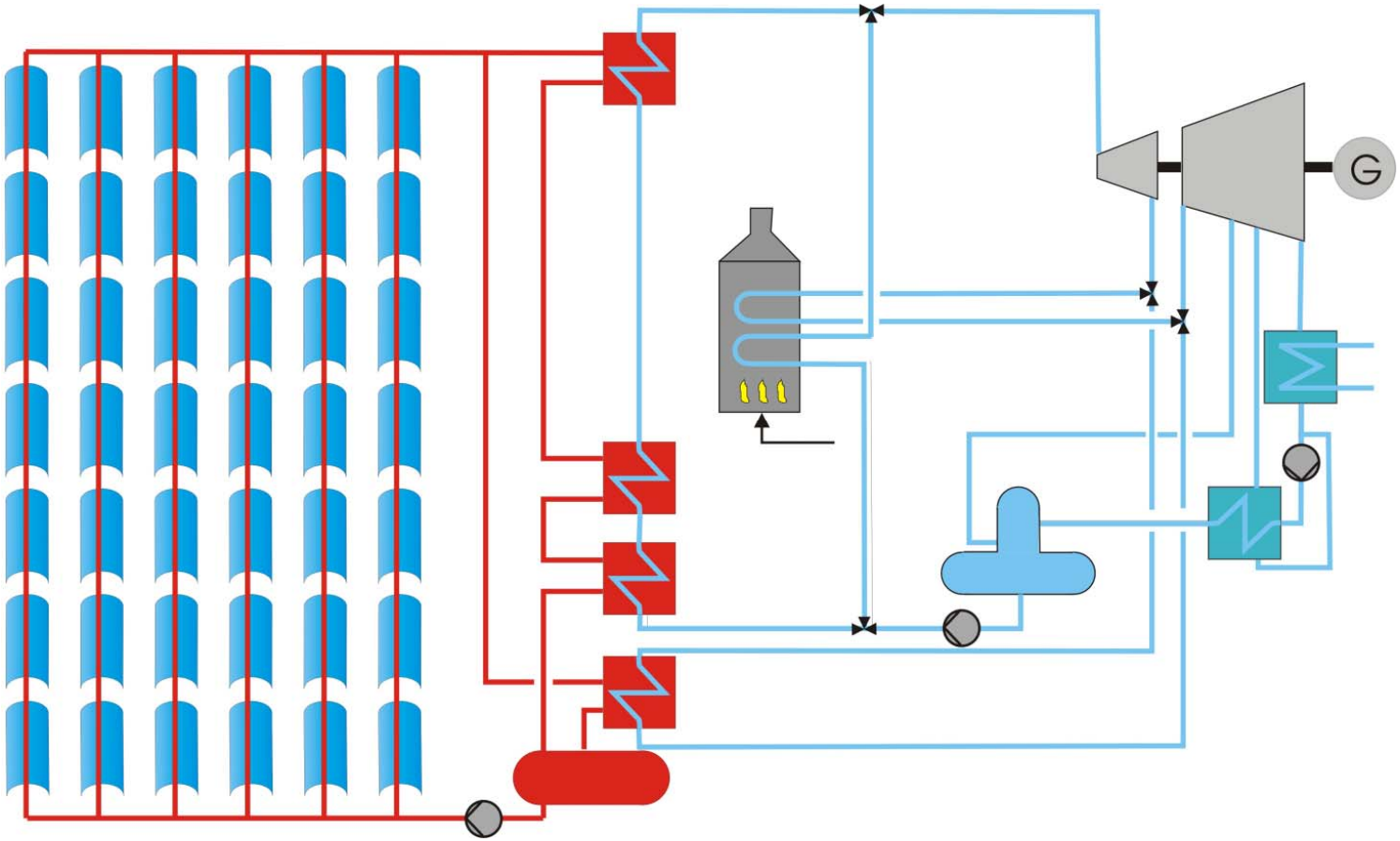
Solarlite: TSE-1

Overview

- Introduction
- DSG History
- DSG Characteristics and two-phase flow
- Plant concepts
- Research Overview
    - Once-through
    - Steam Parameters
    - Operation/Control
    - Storage concepts
- Final Remarks and Outlook

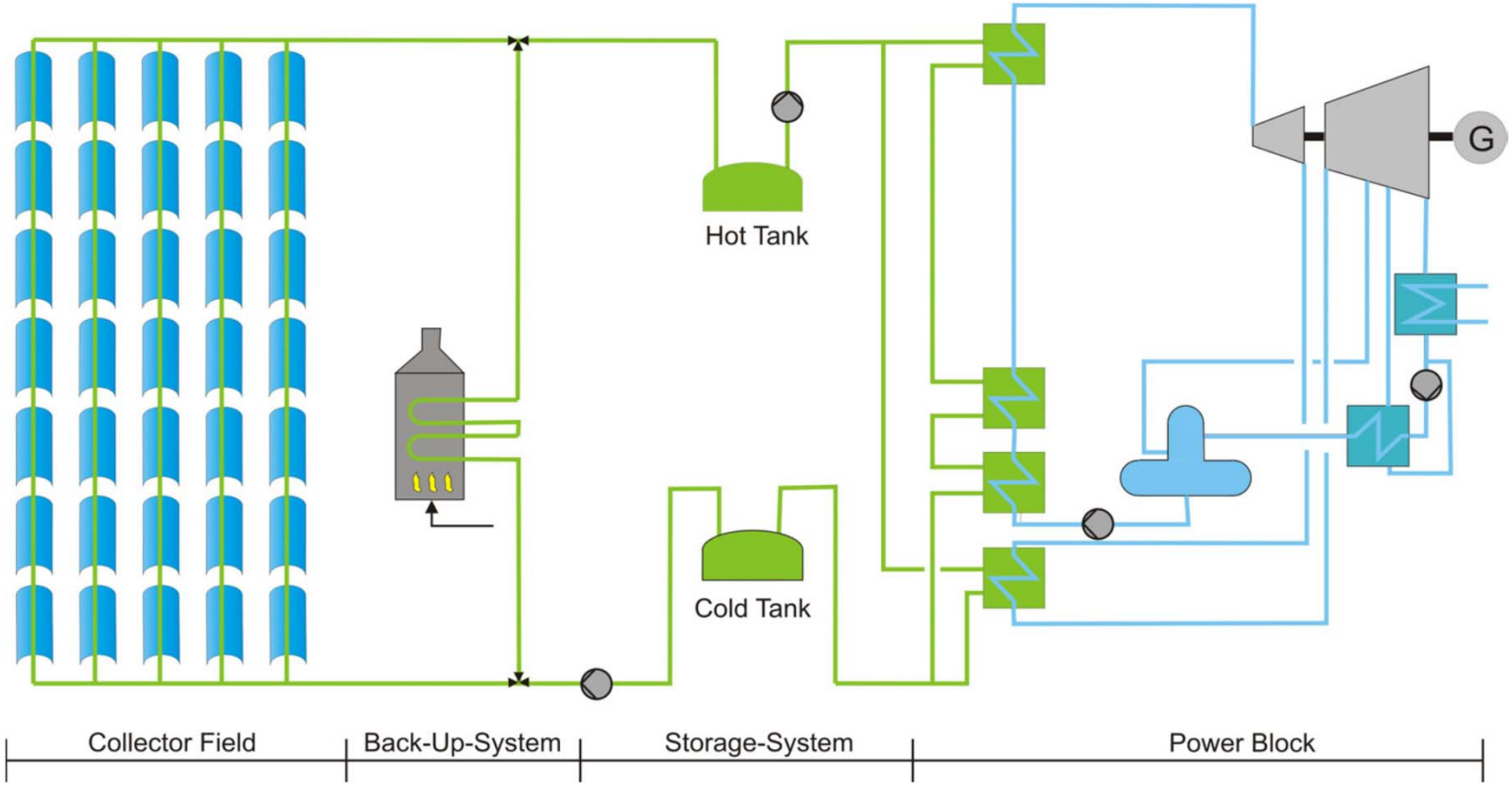
Solarlite: TSE-1

Parabolic Trough Plants with Oil

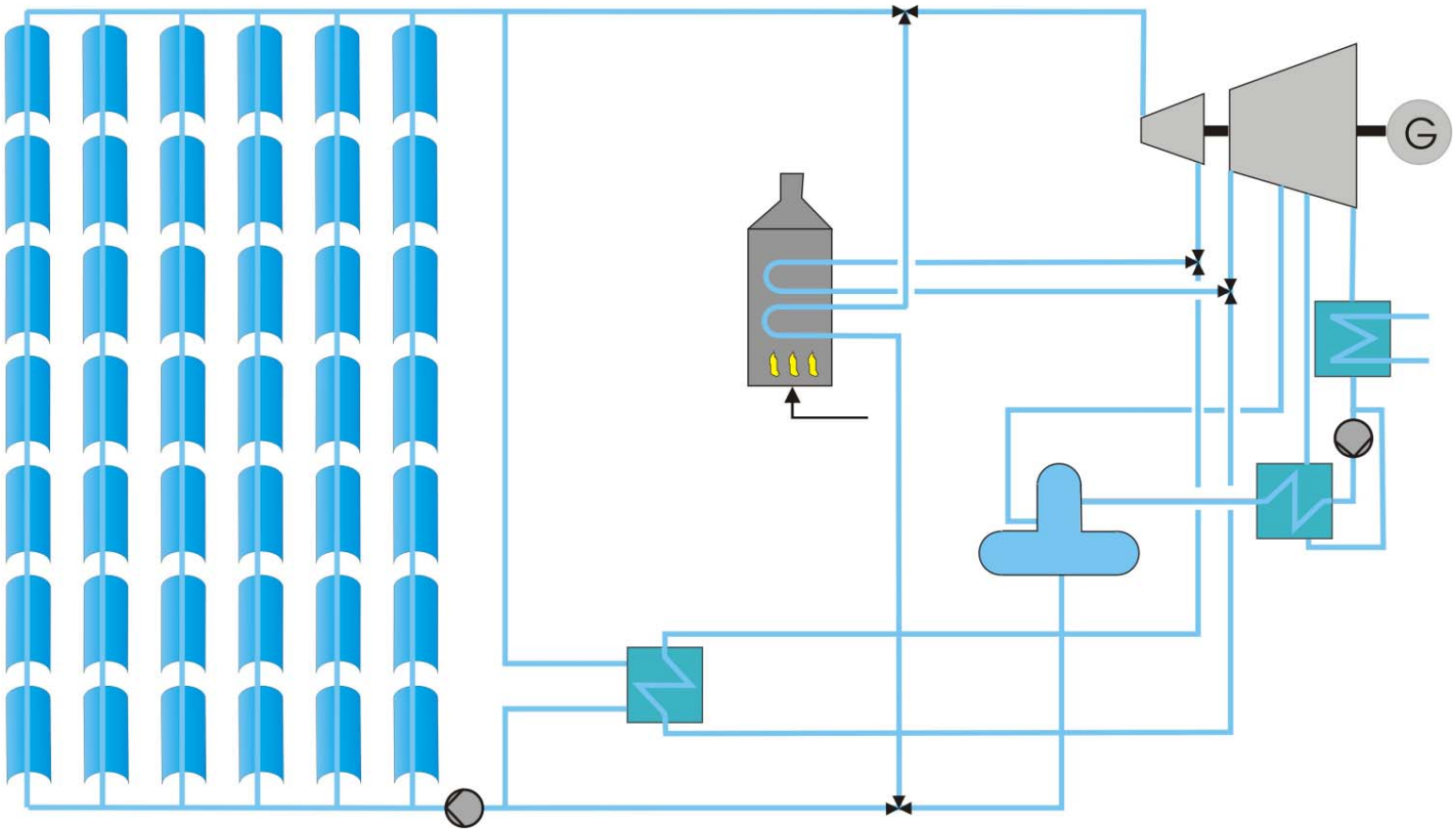


Solarlite: TSE-1

Parabolic Trough Plants with Molten Salt



Parabolic Trough Plants with DSG



Solarlite: TSE-1

DSG Advantages and Drawbacks

Oil

+ Commercially applied
+ One-phase flow
+ Easily scalable

- Heat exchanger batteries
- T < 400°C
- Efficiency/process limit reached
- Hazardous to environment

DSG

+ No heat exchangers
+ High temperatures
+ High efficiency
+ Non-toxic fluid
+ Simple overall configuration

- Two-phase flow
- Higher control effort
- Thermal storage expensive (so far)
- Higher temperature gradients

Milestones in DSG development

The very beginnings – DSG was first!

Shuman Collector

John Ericsson
- New York, USA, 1870 and 1883
- 3.25-m2-aperture collector
- Driving a small 373-W engine.

Frank Shuman
- Meadi, Egypt, 1912-1913
- 5 collectors 62x4m
- driving a steam engine (~40 kW) used to pump water for irrigation

Fernández-García, A., Zarza, E., Valenzuela, L., et al., 2010, "Parabolic-trough solar collectors and their applications," Renewable and Sustainable Energy Reviews, 14, pp. 1695 - 1721.

Milestones in DSG development

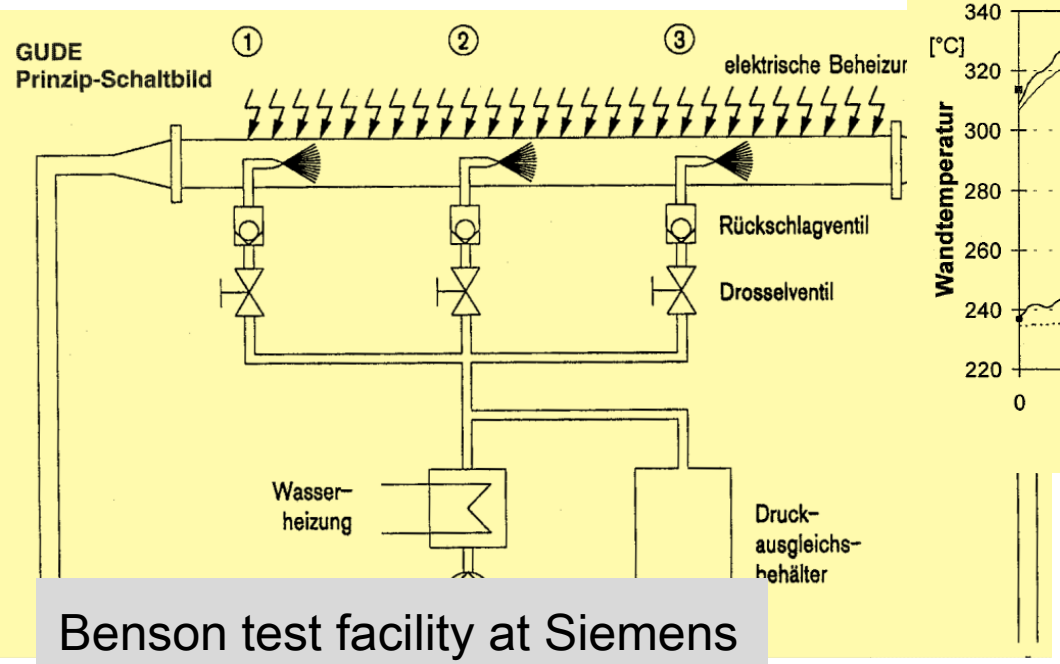
Revival in the 80‘s

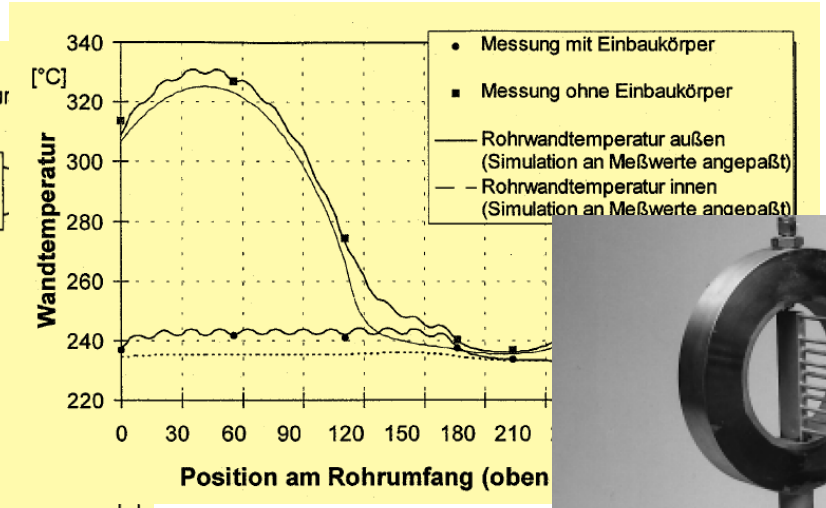
Solar One, Barstow, USA

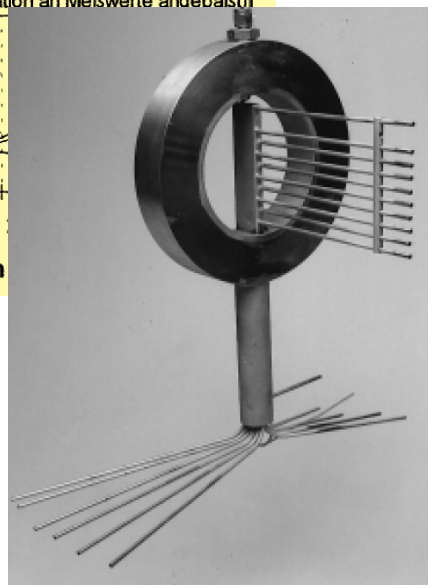
- 10 MWe, 425 °C
- Once-through boiler
- 4 hours storage (sensible)
- In operation 1982-1988

Milestones in DSG development

Experiments with DSG in horizontal tubes



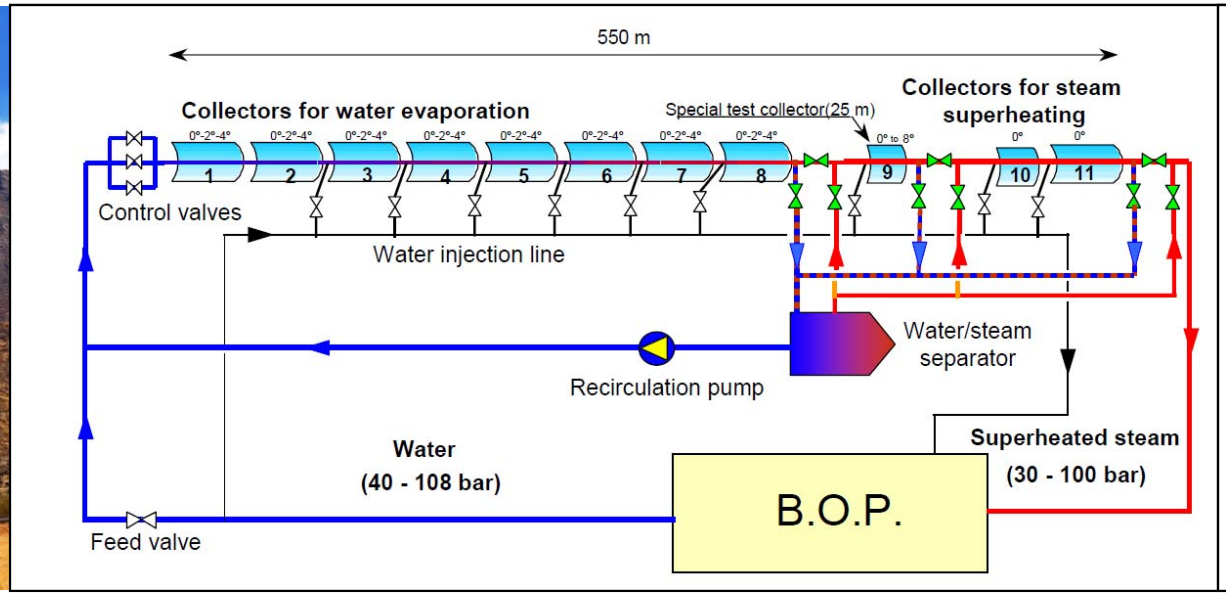


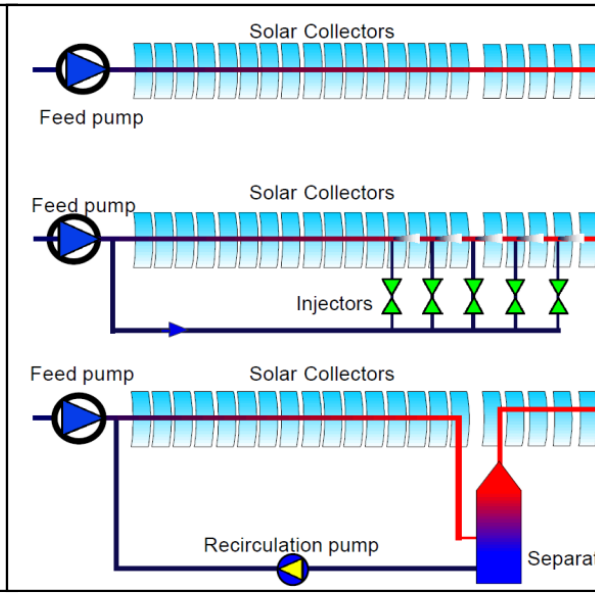


Benson test facility at Siemens

Goebel et al: Direkte Dampferzeugung in Parabolrinnensolarkraftwerken.
Forschungsverbund Sonnenenergie Themen 96/97, page 110 ff

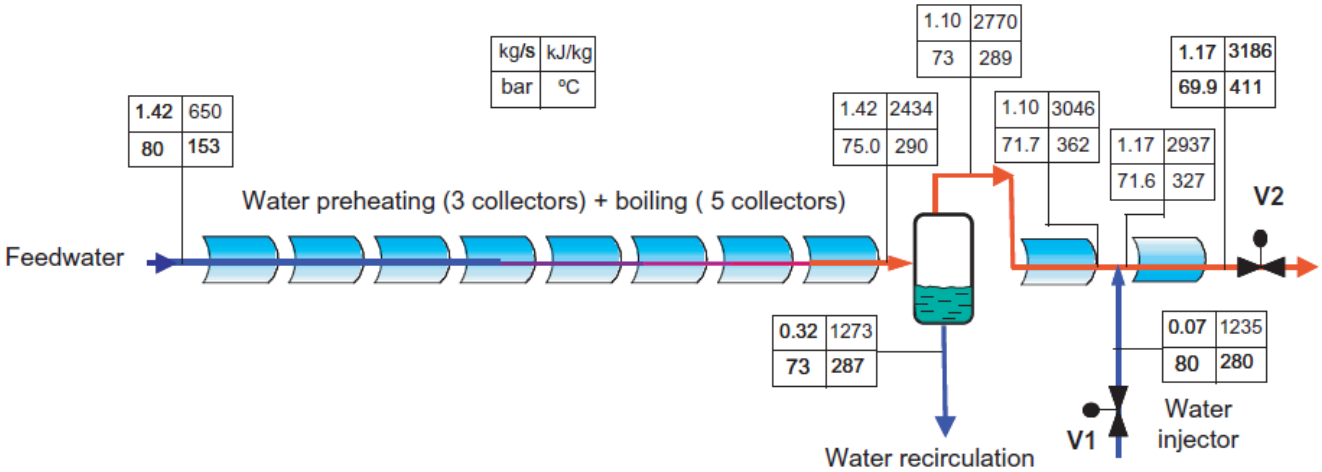
Milestones in DSG development
DISS project: 500 m/100 bar/400 °C





Milestones in DSG development

Planning of demonstration plant



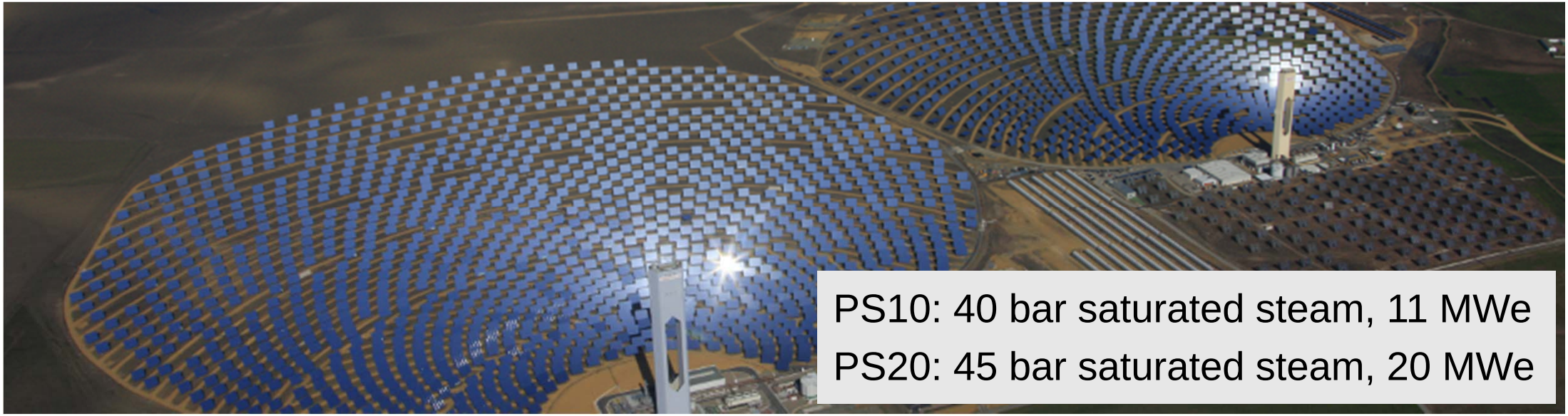
INDITEP

- Application of design tools
- 5 MWe, 410°C / 78 bar
- Recirculation with decentral separators
- Another 200m for DISS

Zarza, E., Rojas, M. E., González, L., et al., 2006, "INDITEP: The first pre-commercial DSG solar power plant," Solar Energy, 80 (10), pp. 1270-1276.

Milestones in DSG development

Commercial tower implementations



PS10: 40 bar saturated steam, 11 MWe

PS20: 45 bar saturated steam, 20 MWe

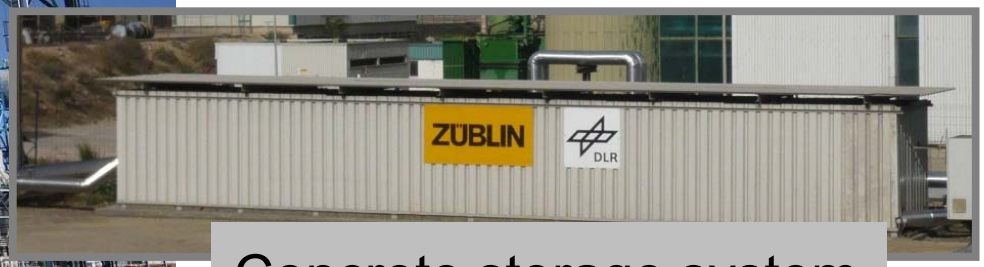
http://www.abengoasolar.com/corp/web/en/nuestras_plantas/plantas_en_operacion/espana/PS10_la_primera_torre_comercial_del_mundo.html

Milestones in DSG development

DSG Component tests at 500 °C

2010/2011
Real-DISS test facility
112 bar / 500 °C

PCM storage system



Concrete storage system

Milestones in DSG development
Linear Fresnel plants

PE-1: 1 MW, 55 bar, saturated steam

PE-2: 30 MW, 55 bar, saturated steam

Both plants with Linear Fresnel technology by Novatec Solar

Source: DLR

Milestones in DSG development

Linear Fresnel plants

Kimberlina 5 MWe
106 bar, 400 °C
(higher values announced)
Technology by Areva Solar

Source: Areva Solar

Milestones in DSG development

The first parabolic trough plant with superheating

TSE-1, Thailand

5 MWe

34 bar, 340 °C

Technology by Solarlite

DSG Status – It‘s commercial!

Topics for industry:

- Higher steam parameters (up to 110 bar /500 °C)
- Parameter Optimization → Pressure and temperature vs. Piping cost
- Improvements in plant configurations and costs

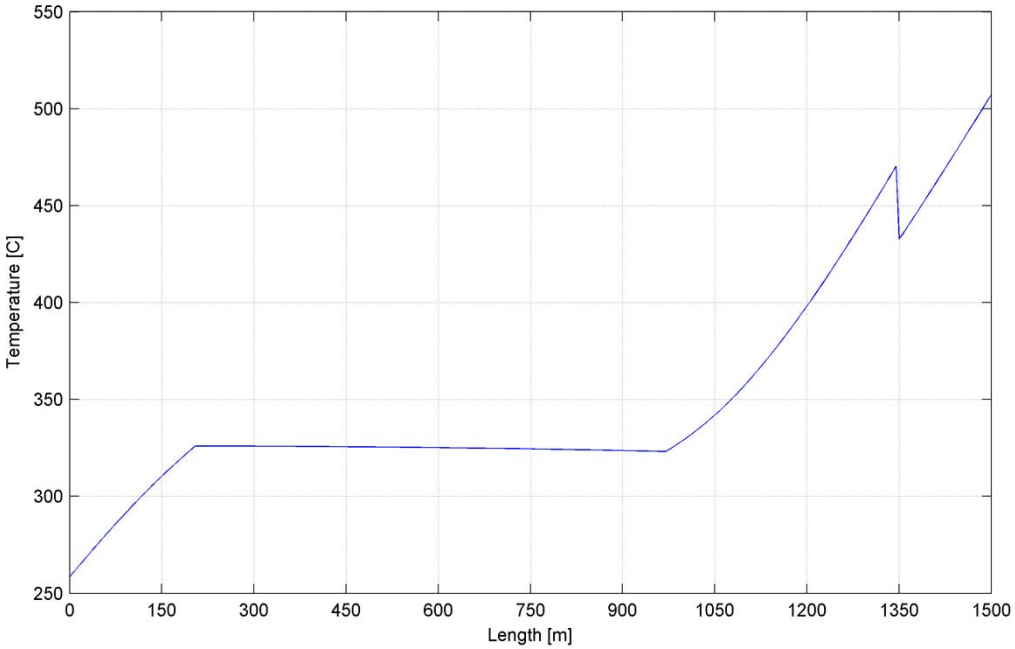
Topics for R&D:

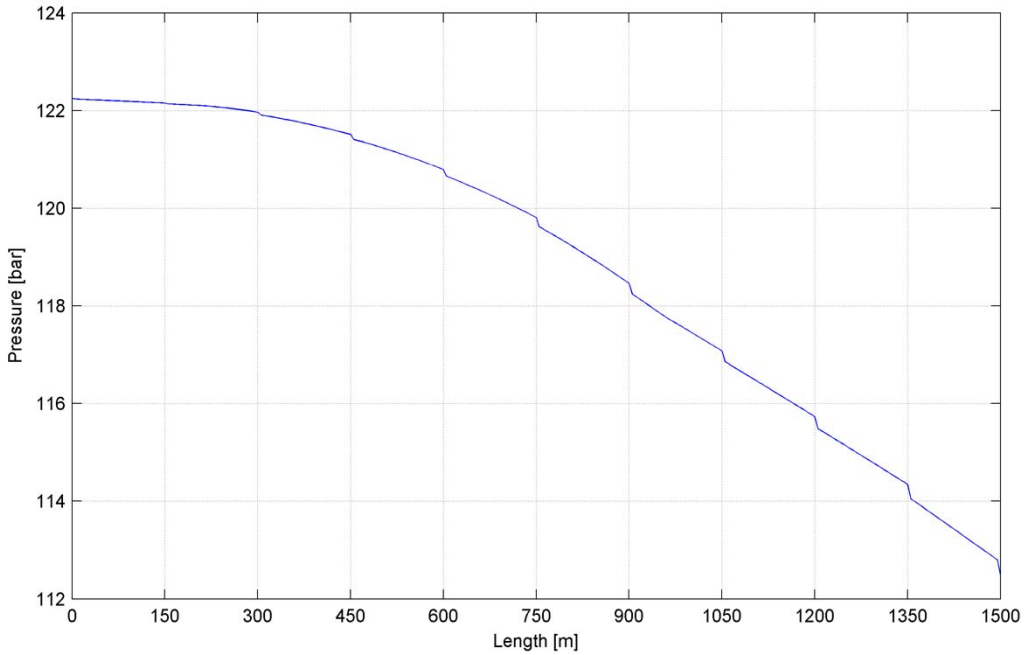
- Solar Field Optimization → Optimized recirculation, once-through
- Operation Optimization → Start-up, Control
- Thermal Energy Storage → Costs, Performance
- Plant integration options → Hybrid, TES

Loop Characteristics > What it’s all about…

Loop Characteristics > Temperature/pressure

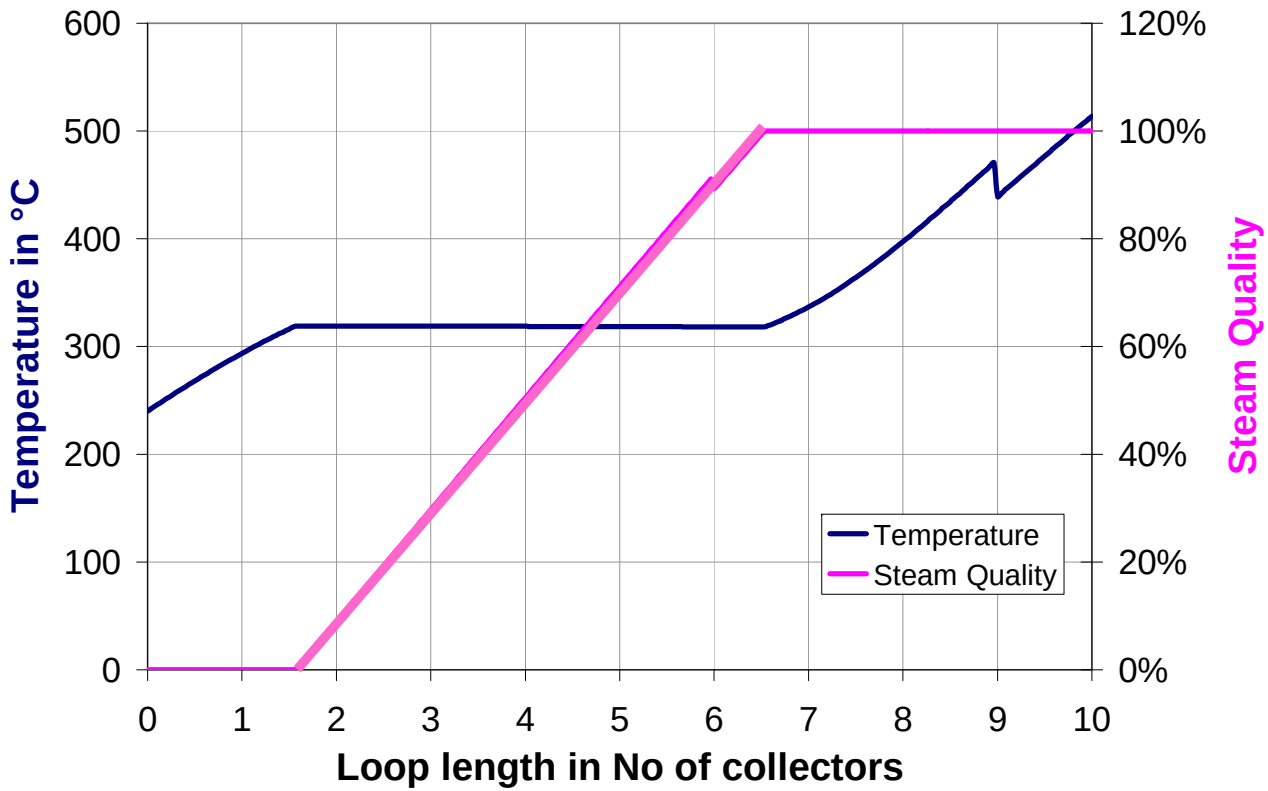
- Temperature and pressure along loop (1500m, 500°C/112 bar outlet)



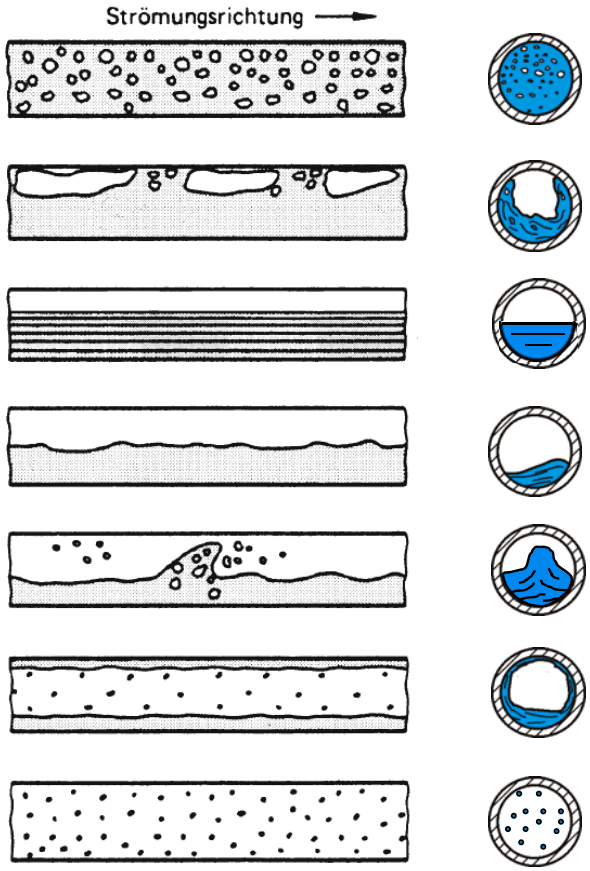


Solarlite: TSE-1

Loop Characteristics > Temperature/Steam Quality



Flow Patterns in horizontal tubes



Bubble Flow

Plug Flow

Stratified Flow → To be avoided

Wavy Flow

Slug Flow

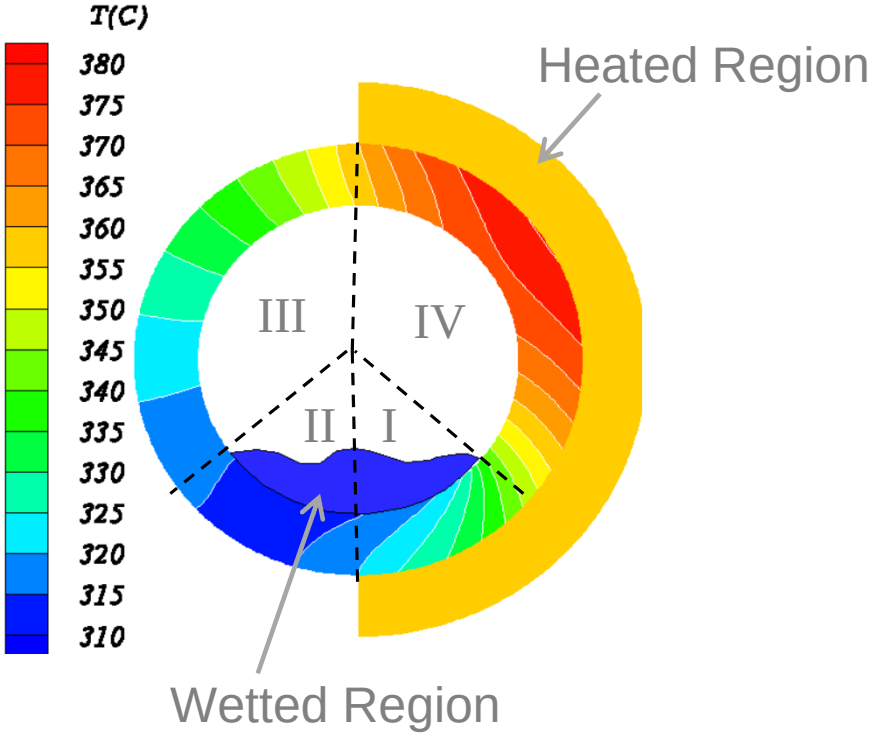
Annular Flow → Desired

Drop/Spray Flow

Based on VDI Heat Atlas, 10. Aufl. 2006, Hbb

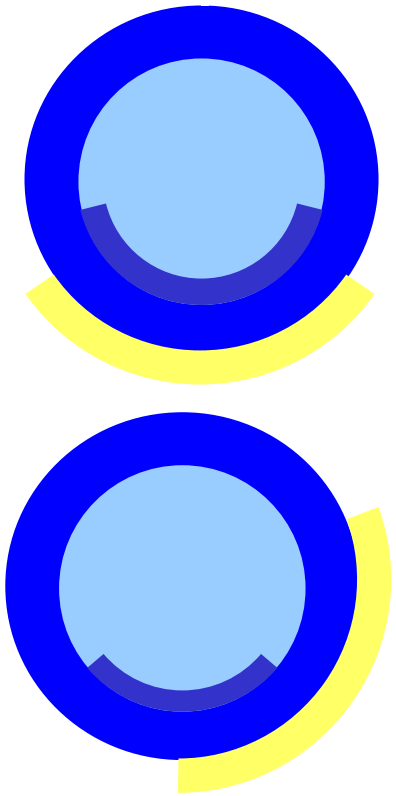
Loop Characteristics > Temperatureprofile

- Four regions
  - I. Wetted– heated
  - II. Wetted– not heated
  - III. Dry – not heated
  - IV. Dry – heated
- Asymmetric temperature profile around cross section



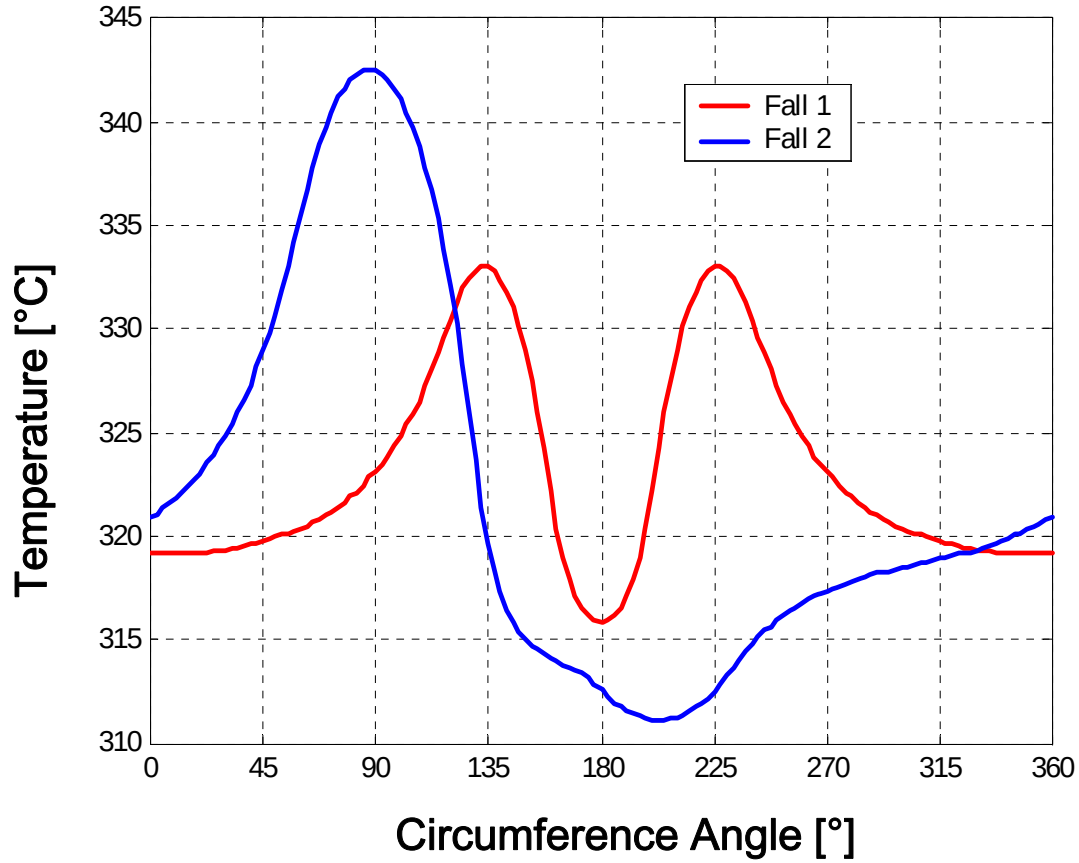
Two-phase flow in horizontal pipes

Internal heat transfer



case 1

case 2

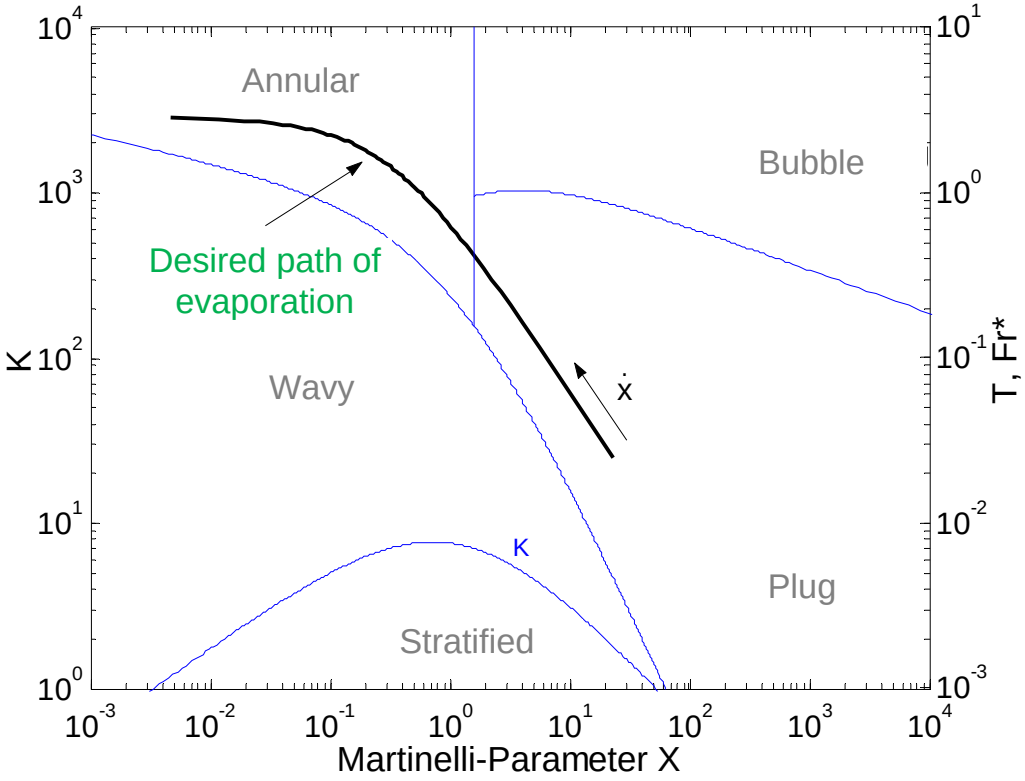


Loop Characteristics > Do you understand?

- Question of the day
- Which is the most desirable flow pattern in DSG loops with high steam quality?
- Answer:
  Annular Flow
  due to its complete wetted inner surface.

Two-phase flow in horizontal pipes

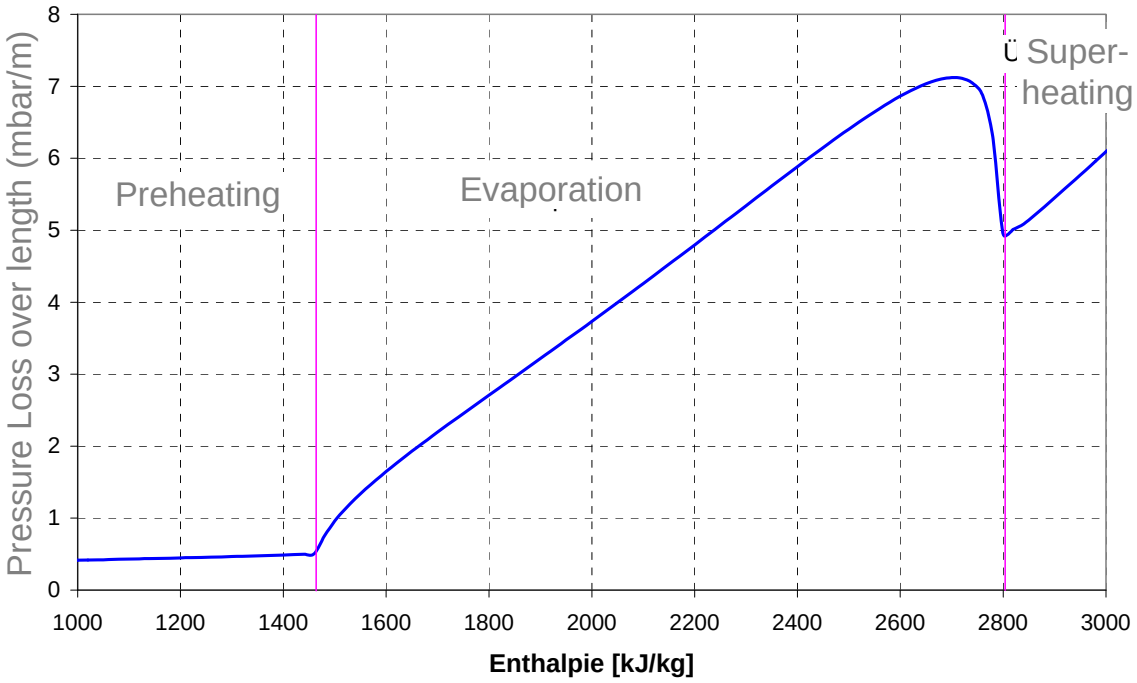
Flow pattern map

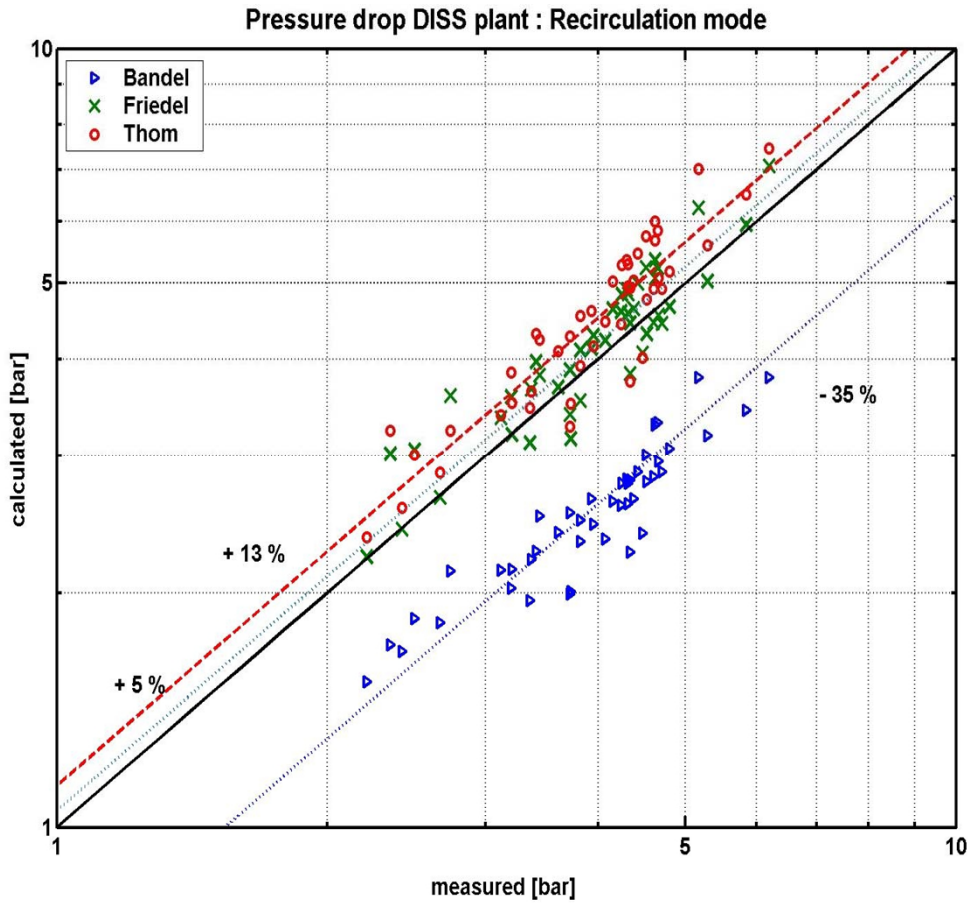


Taitel, Y., and Dukler, A. E., 1976, "A model for predicting flow regime transitions in Horizontal and near horizontal gas-liquid flow," AIChE Journal, 22 (1), pp. 47-55.:

Two-phase flow in horizontal pipes

Pressure loss





Plant Concepts > How you could run DSG plants

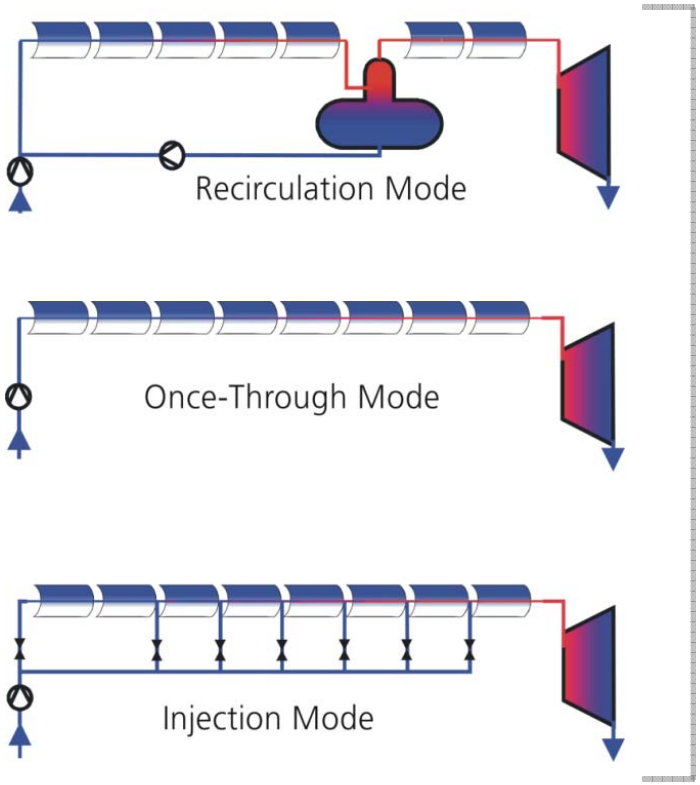
Solarlite: TSE-1

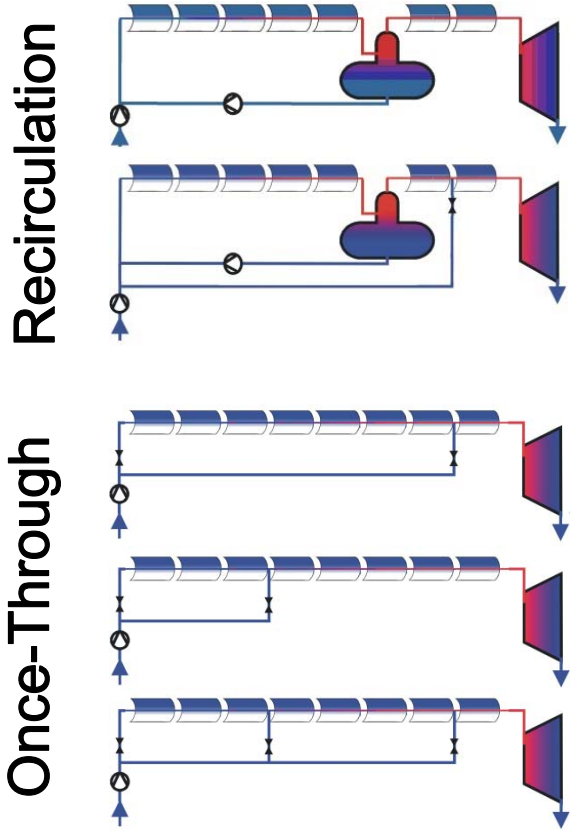
Plant Concepts > Classical approaches

Recirculation

Once-Through (classic)

Injection

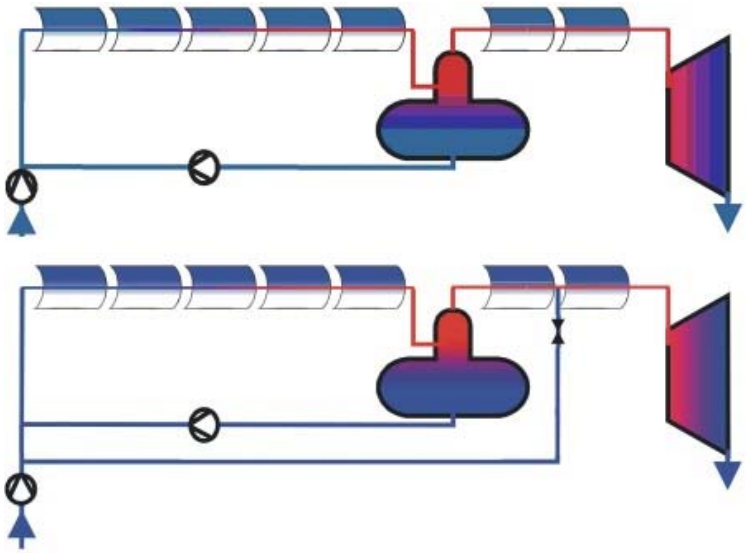




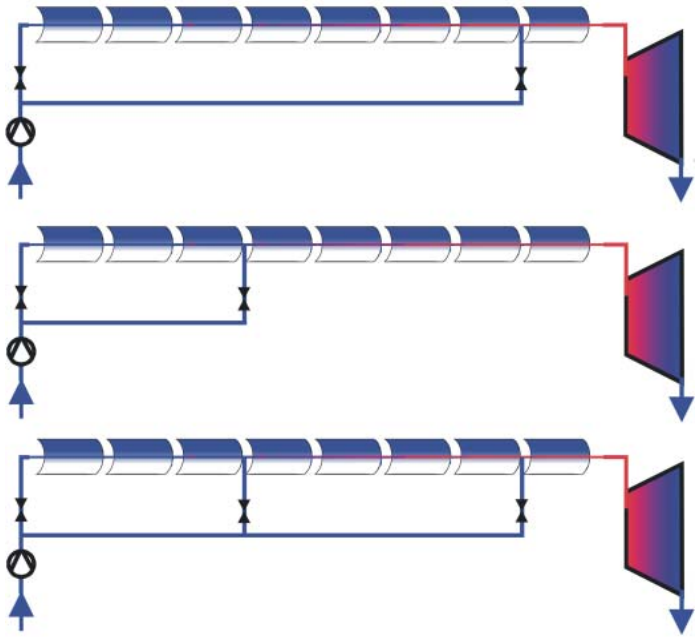
Eck, M., and Zarza, E., 2002, "Assessment of Operation Modes for Direct Solar Steam Generation in Parabolic Troughs," 11th SolarPACES, Zurich, Switzerland

Plant Concepts > State-of-the-Art Concepts

Recirculation



Once-Through



Plant Concepts > State-of-the-Art Comparison

Recirculation

+ Very robust operation
+ Commercially applied

- Relatively high investment
- Relatively high design effort

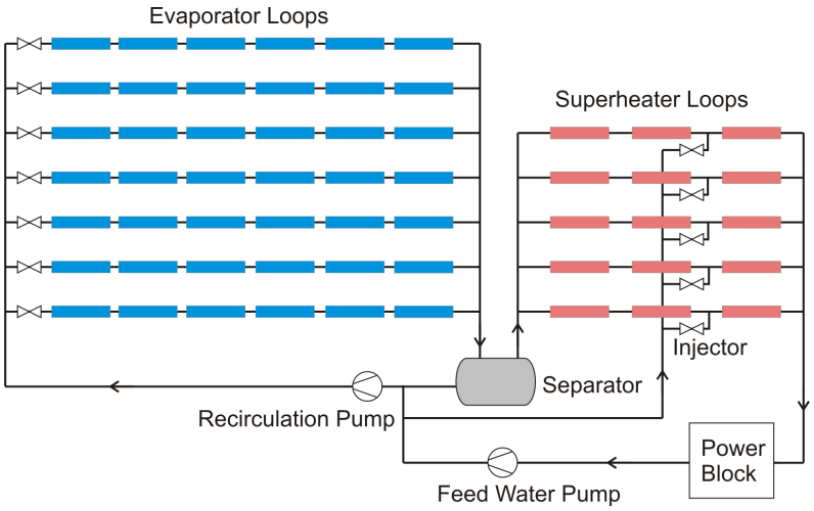
Once-Through

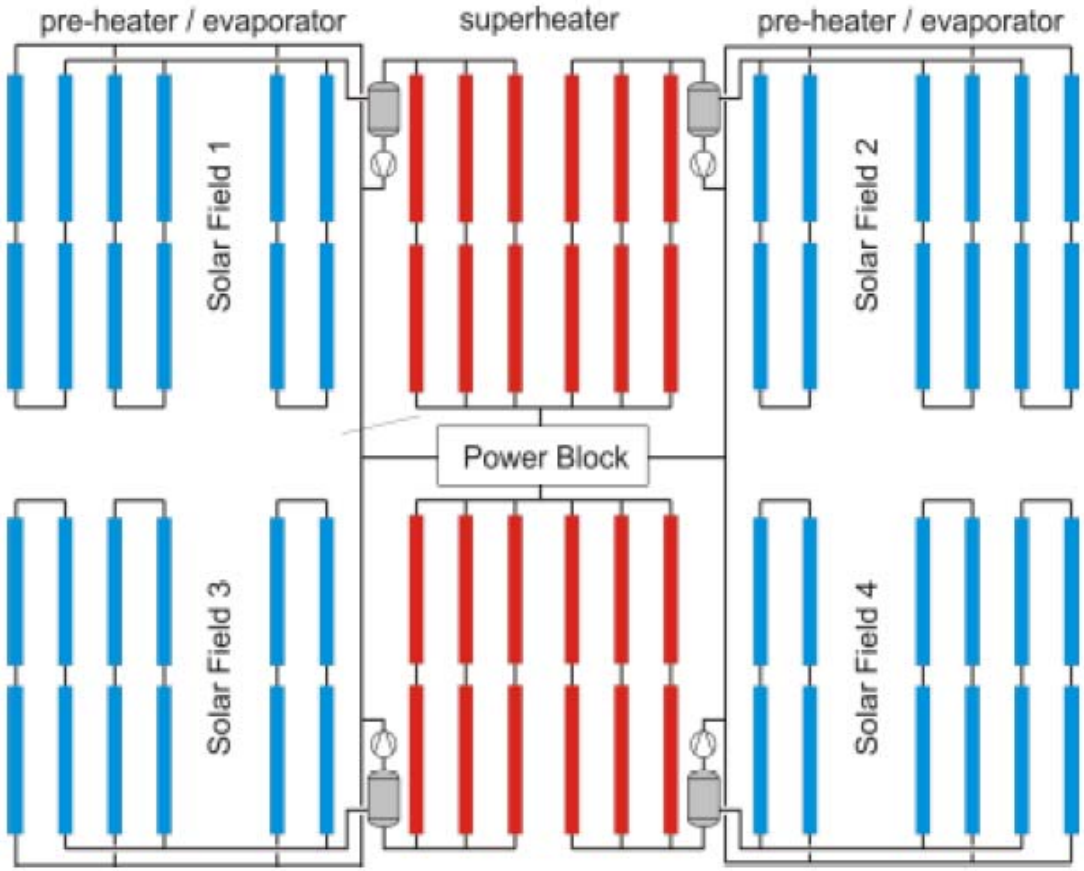
+ Easily scalable
+ Fast start-up
+ Low investment

- Not that robust
- End of evaporation not fixed

Based on: Eck, M., and Zarza, E., 2002, "Assessment of Operation Modes for Direct Solar Steam Generation in Parabolic Troughs," 11th SolarPACES Intern. Symposium on Concentrated Solar Power and Chemical Energy Technologies, Zurich, Switzerland

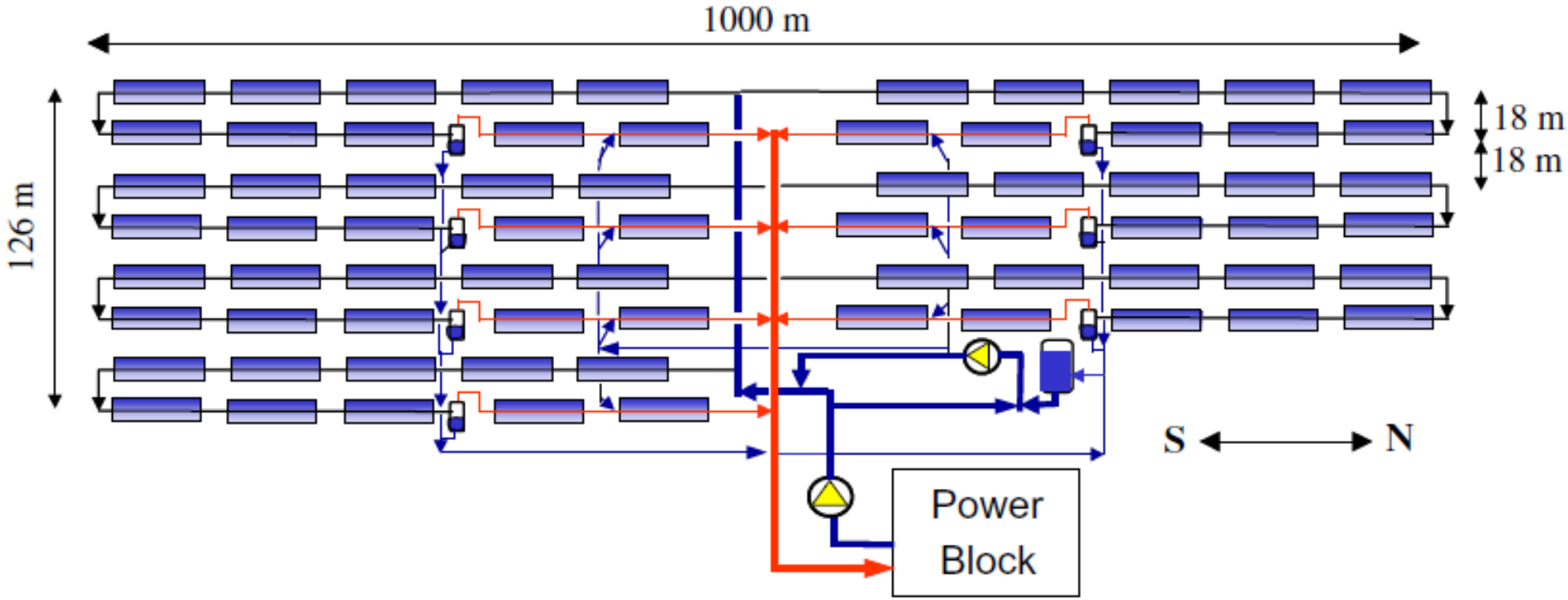
Plant Concepts > Recirculation with central field separators





DLR, Feldhoff/Hirsch

Plant Concepts > Recirculation with decentral separators



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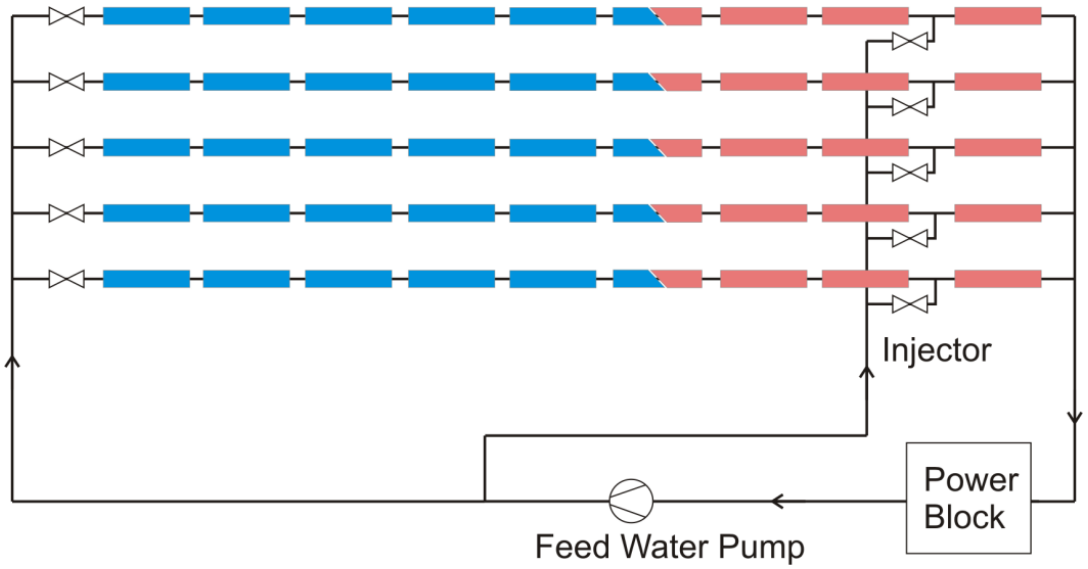
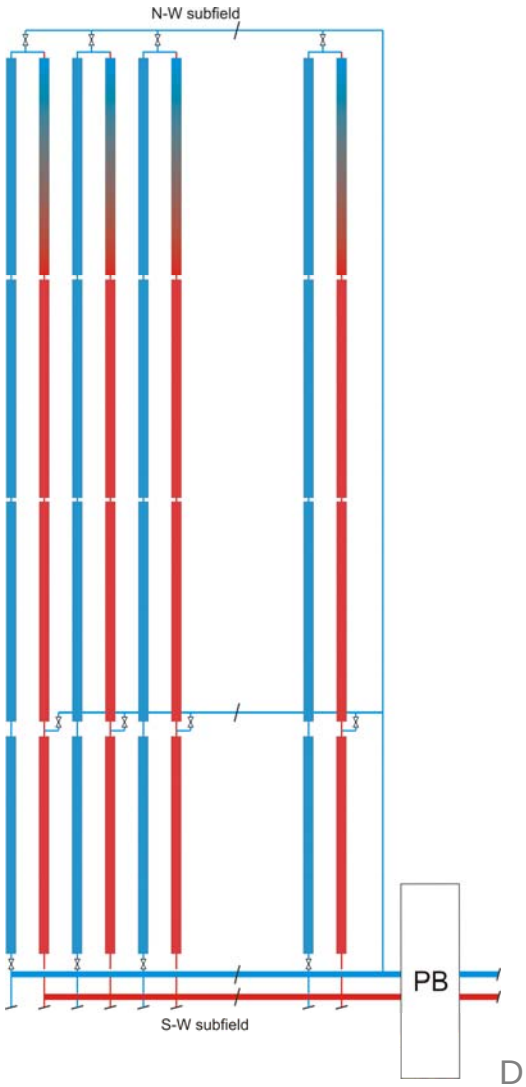
Plant Concepts > Once-Through

- With 1 or 2 injections
- Only one type of loop

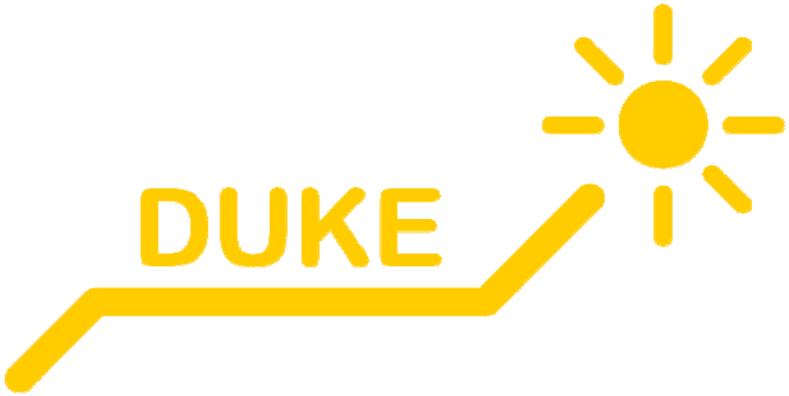




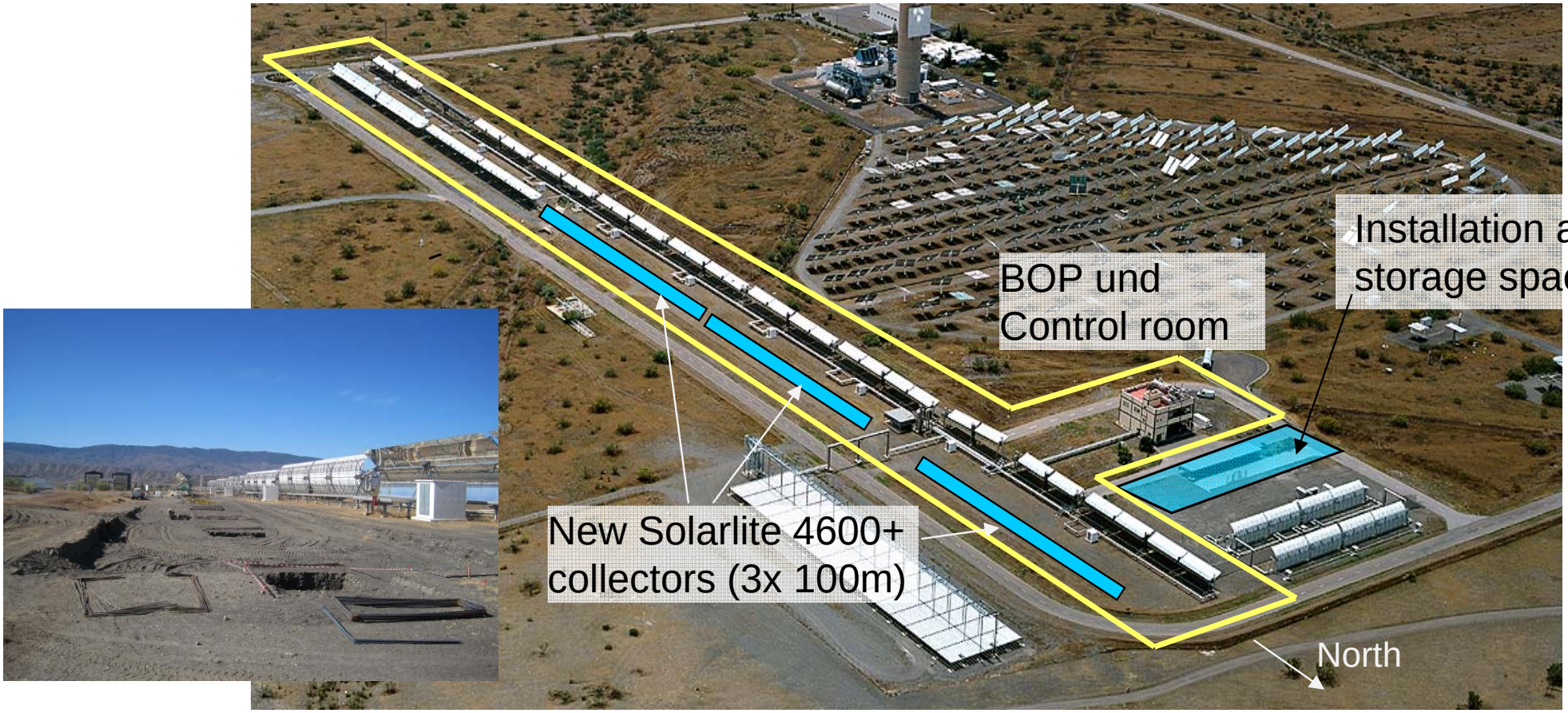
Once-through > The better DSG concept?

Once-through > The DUKE Project

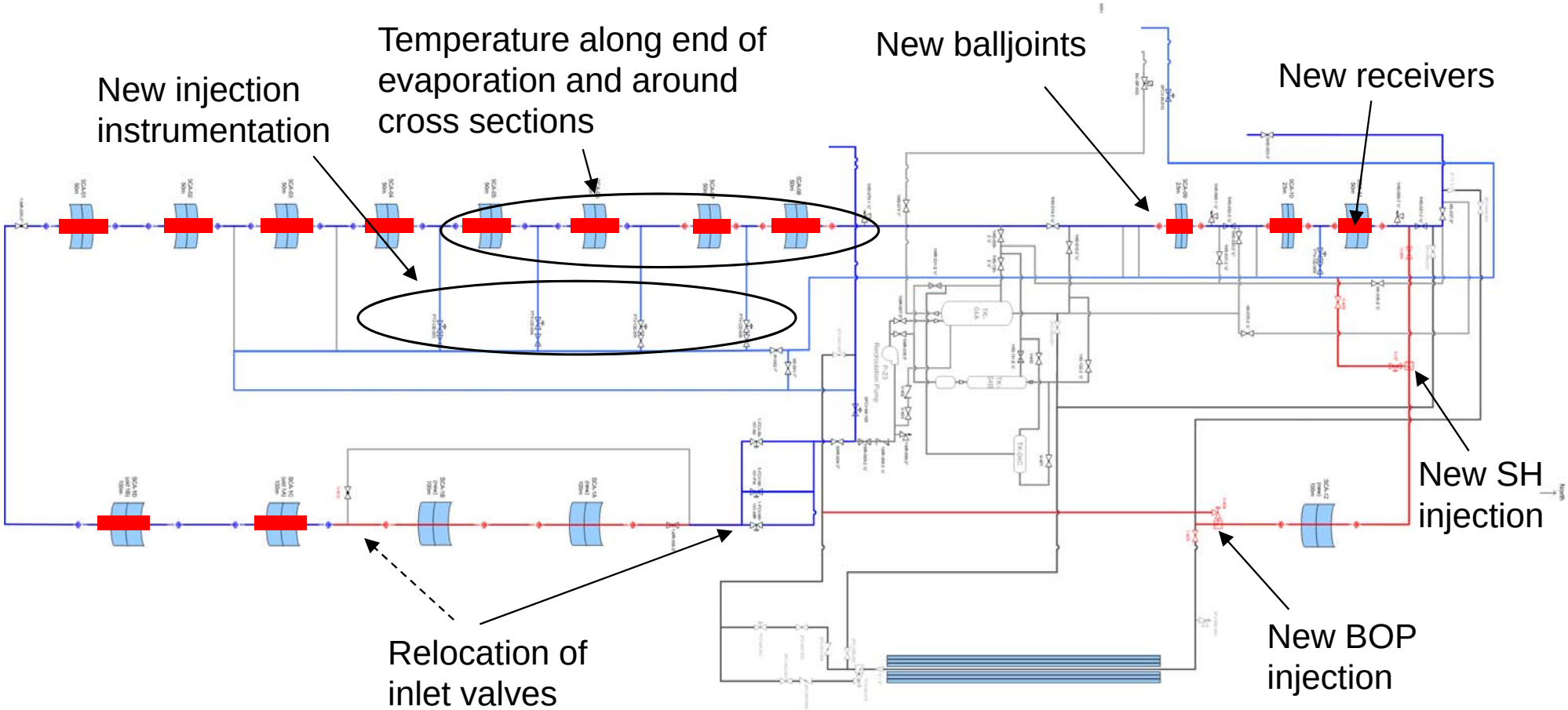
- DUKE: Durchlaufkonzept – Entwicklung und Erprobung (Once-Through Concept Development and Demonstration)
- Goals
  - Analysis and demonstration of Once-through concept under real irradiation conditions
- Partner
  - DLR & Solarlite GmbH
  - Together with CIEMAT
- Period:
  - May 1, 2011 to April 30, 2014



Once-through > Demonstration at DISS Facility

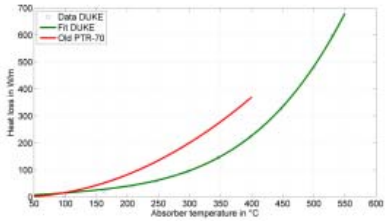


Once-through > Main Changes DISS Solar Field



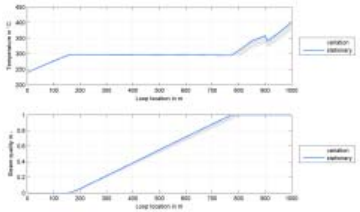
Once-through > Main Demonstration Experiments

- Component qualification



- Design and validation of dynamic models

- Test and validation of control concepts



→ System evaluation of once-through concept

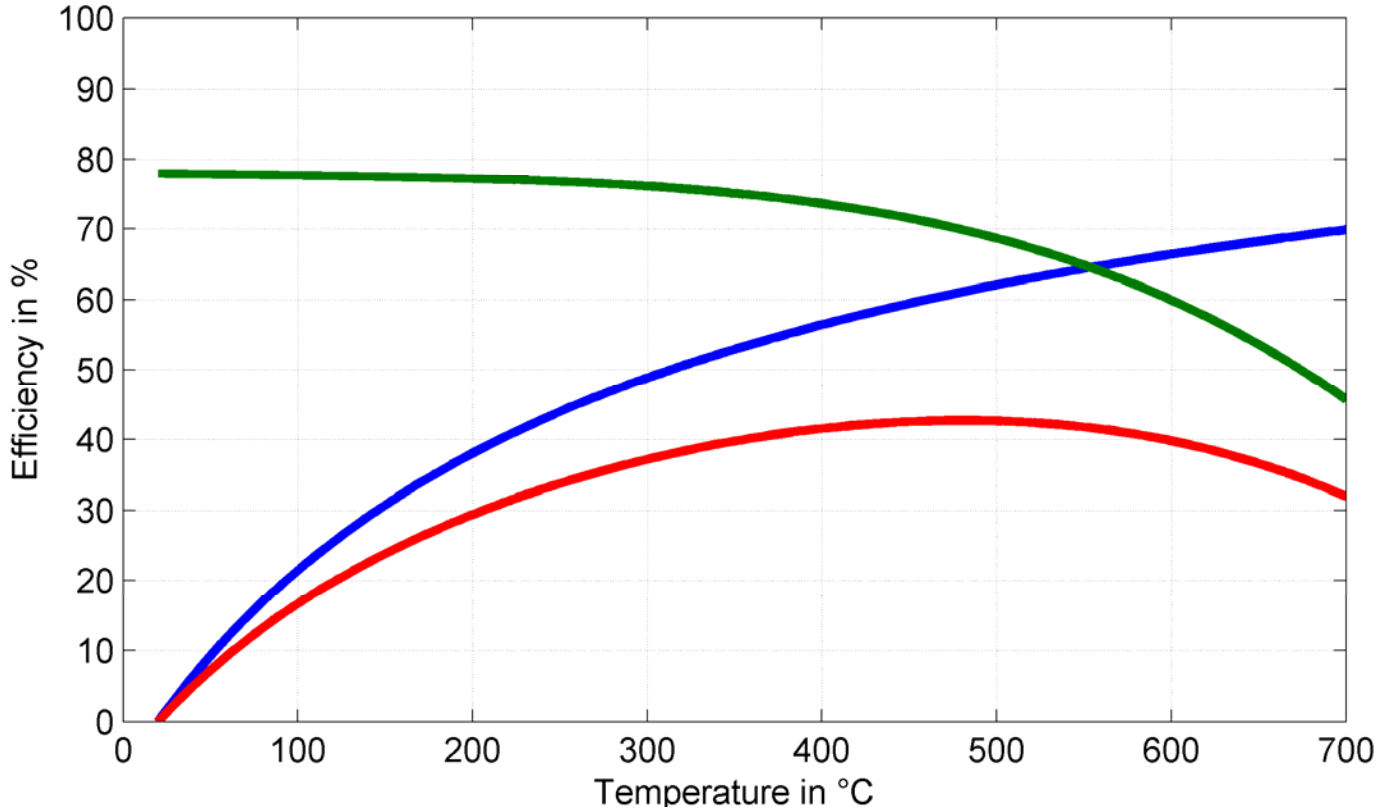
Parameter Optimization > One step ahead…

Parameter Optimization > Why that?

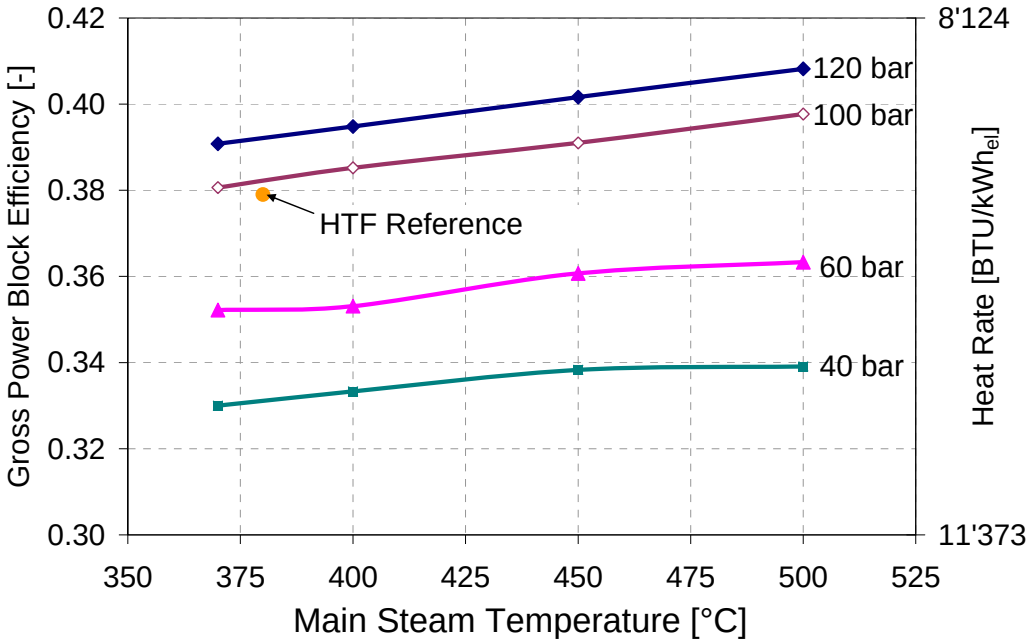
- Power Block: Carnot efficiency increases with temperature
- Solar field: efficiency decreases with temperature

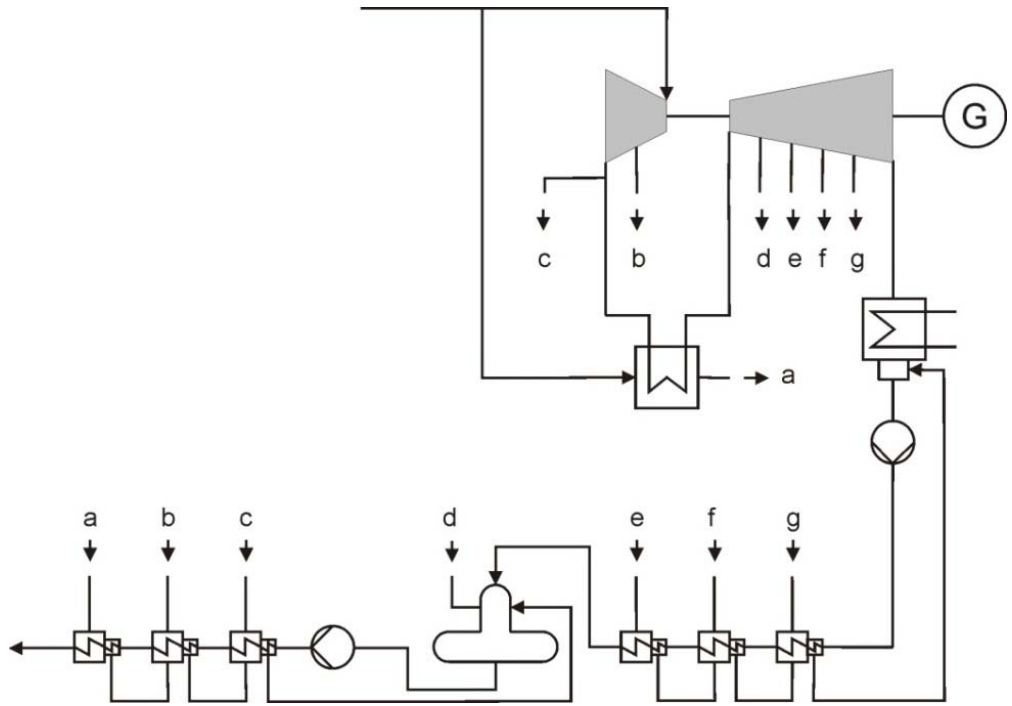
→ Find the optimum

→ Look at real-life thermodynamics and costs together!



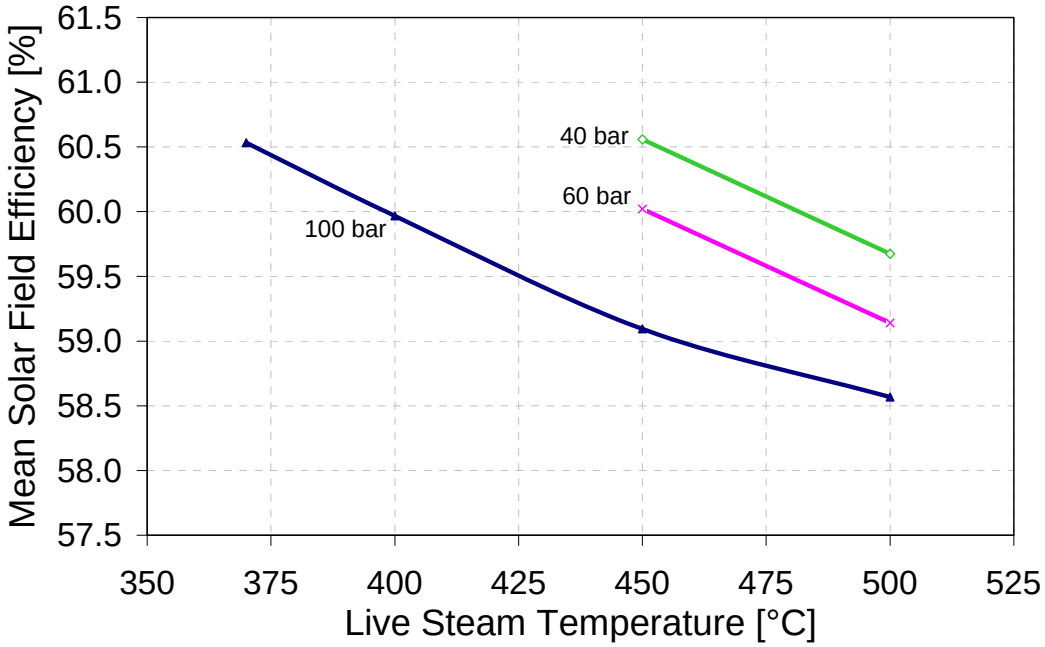
Parameter Optimization > Power Block

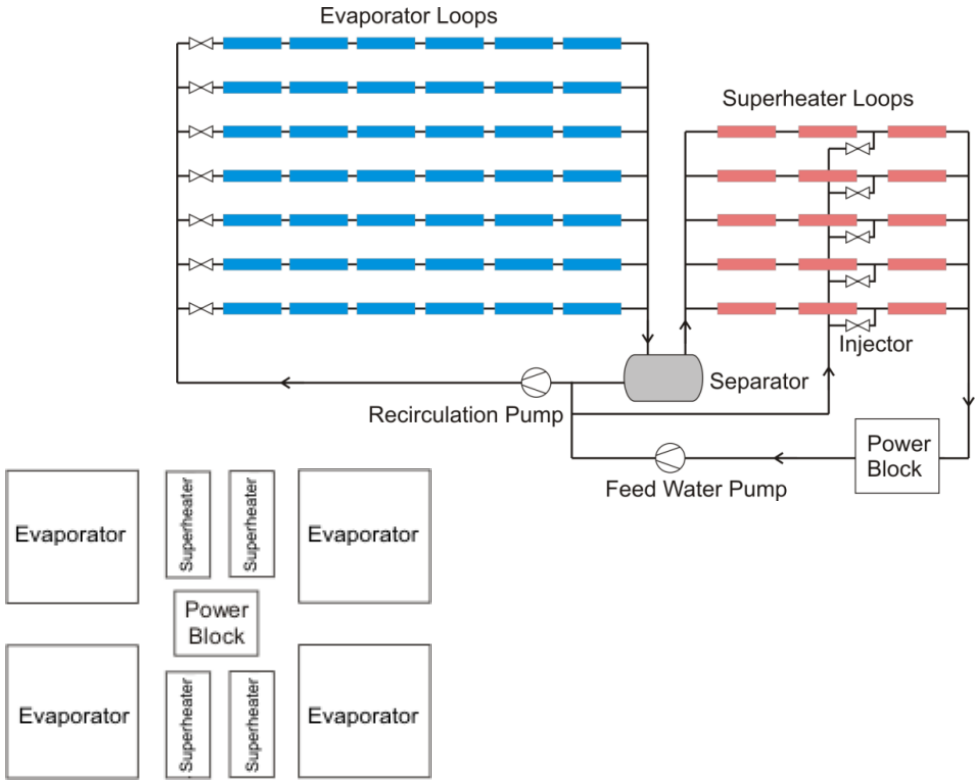




Feldhoff, J. F., Benitez, D., Eck, M., et al., 2010, "Economic Potential of Solar Thermal Power Plants With Direct Steam Generation Compared With HTF Plants," Journal of Solar Energy Engineering, 132 (4), pp. 041001-9.

Parameter Optimization > Solar Field (Rec.)





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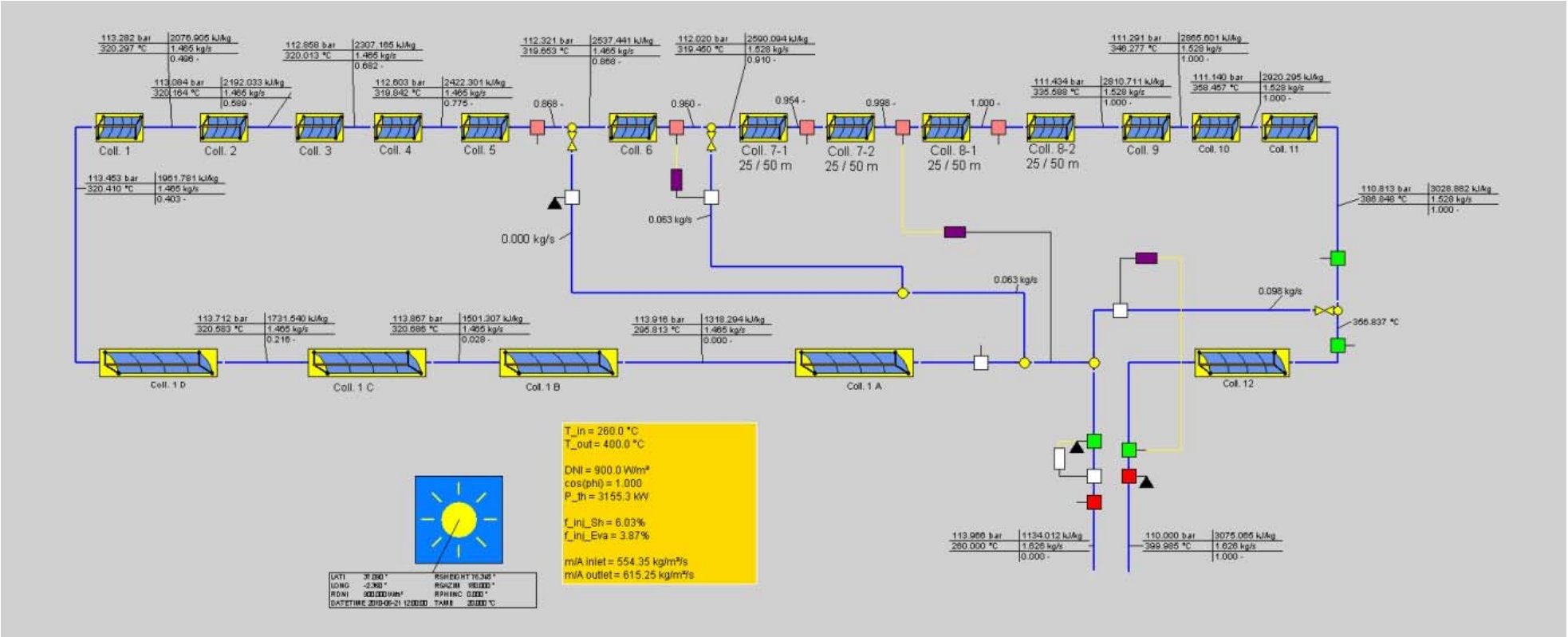
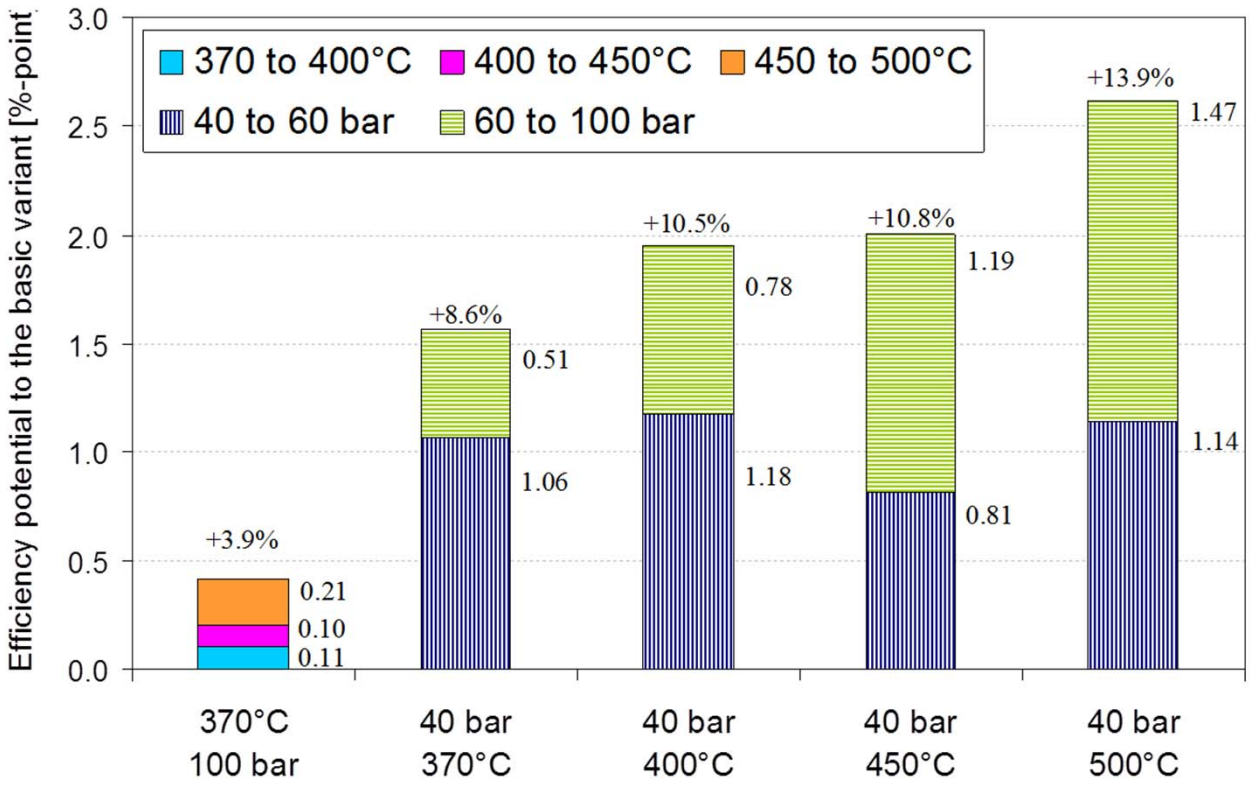
Parameter Optimization > Heat Balance Tool



Parameter Optimization > Overall efficiencies



- Comparison of annual net efficiencies
- Thermodynamics: pressure increase more efficient than temperature increase
- Costs: piping for higher pressure more expensive

Feldhoff, J. F., Benitez, D., Eck, M., et al., 2010, "Economic Potential of Solar Thermal Power Plants With Direct Steam Generation Compared With HTF Plants," Journal of Solar Energy Engineering, 132 (4), pp. 041001-9.

System Analysis > Comparison with oil trough

Annual Yield Results for 100 MWe, Daggett (USA), 9h of thermal energy storage (TES):

- DSG solar field size -5.3 %
- DSG net electricity output +2.5 to +2.9 %
- Net plant efficiency +8.3 %

For 100 MW_{el}, 9h TES	Unit	Mean Results DSG	Mean Results Oil	Flagsol DSG to Oil	DLR DSG to Oil
Annual DNI to SF	GWh/y	2'489.2	2'629.1	-5.3%	-5.3%
SF thermal energy	GWh/y	1'037.4	1'115.1	-7.1%	-6.9%
Gross electricity	GWh/y	405.7	410.7	-1.5%	-0.9%
Net electricity	GWh/y	371.5	362.1	+2.5%	+2.7%
Global net electricity	GWh/y	367.8	358.1	+2.5%	+2.9%
Online auxiliaries	GWh/y	29.1	43.1	-33.5%	-31.4%
SF mean efficiency	-	41.7%	42.4%	-1.8%	-1.6%
PB mean gr. efficiency	-	39.1%	36.8%	+6.0%	+6.4%
Net plant efficiency	-	14.9%	13.8%	+8.3%	+8.4%

Feldhoff, J. F., Schmitz, K., Eck, M., et al., 2012, "Comparative system analysis of direct steam generation and synthetic oil parabolic trough power plants with integrated thermal storage," Solar Energy, 86 (1), pp. 520-530.

DLR

System Analysis > Cost Comparison to Oil Trough

- 100 MWe, 9h TES, Daggett/USA
- Large solar fields sizes (450 MWth and more) are close too current design pressure limits
  → Choose DSG for sizes up to about 50 MWe and long term storage
- TES not yet commercially available
  → Concepts under development
  → Short term projects should focus on short term storage or hybridisation
  → Oil trough without TES at least 5-10% more expensive than DSG

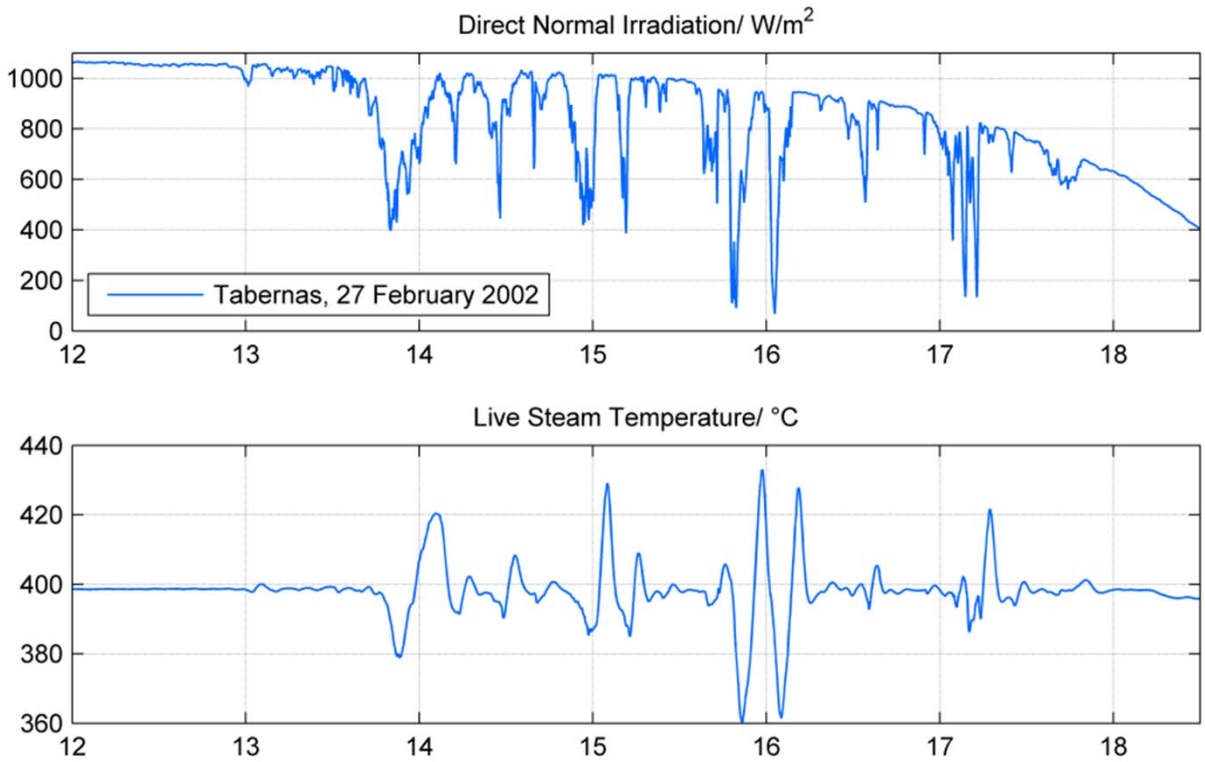
Feldhoff, J. F., Schmitz, K., Eck, M., et al., 2012, "Comparative system analysis of direct steam generation and synthetic oil parabolic trough power plants with integrated thermal storage," Solar Energy, 86 (1), pp. 520-530.

Control > The secret to better performance

Control > Solar Field

- One loop simulated
- Cascaded superheating temperature controller

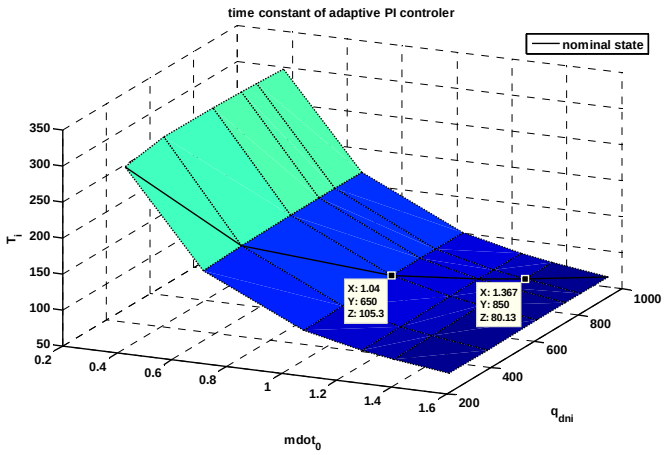
→ Higher temperature gradients than in normal multiple loop plant

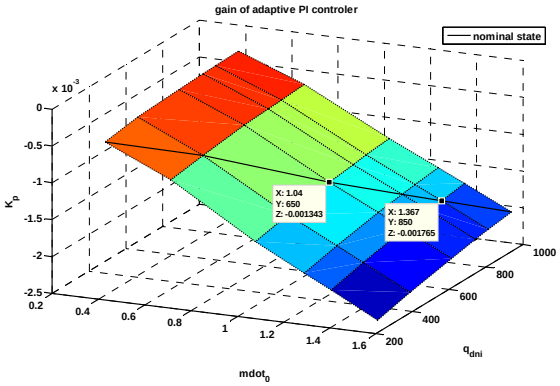


Birnbaum, J., Feldhoff, J. F., Fichtner, M., et al., 2011, "Steam temperature stability in a direct steam generation solar power plant," Solar Energy, 85 (4), pp. 660-668.

Control > Adaptive Controllers

- Adaptive PI controllers with DNI-dependent feedforward are reliable for recirculation and injection mode [1, 2]





Parameter range for adaptive PI controller

[1]: Valenzuela, L., Zarza, E., Berenguel, M., et al., 2005, "Control concepts for direct steam generation in parabolic troughs," Solar Energy, 78 (2), pp. 301-311.
[2]: Eck, M., 2001, Die Dynamik der solaren Direktverdampfung und Überhitzung in Parabolrinnenkollektoren, VDI Verlag Düsseldorf.

Graphics: DLR, Feldhoff/Trebing

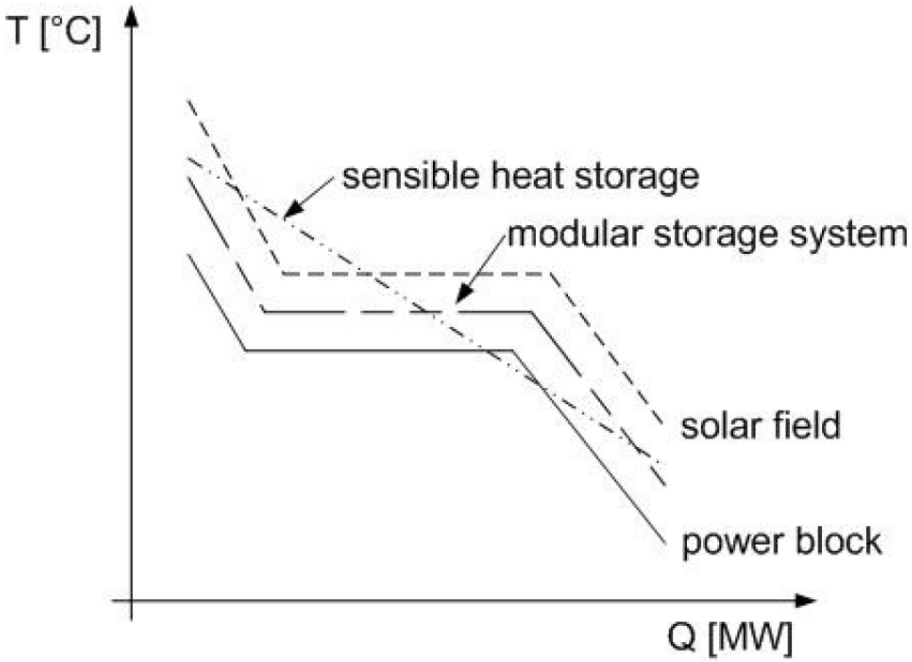
Control > Experience from real recirculation plants

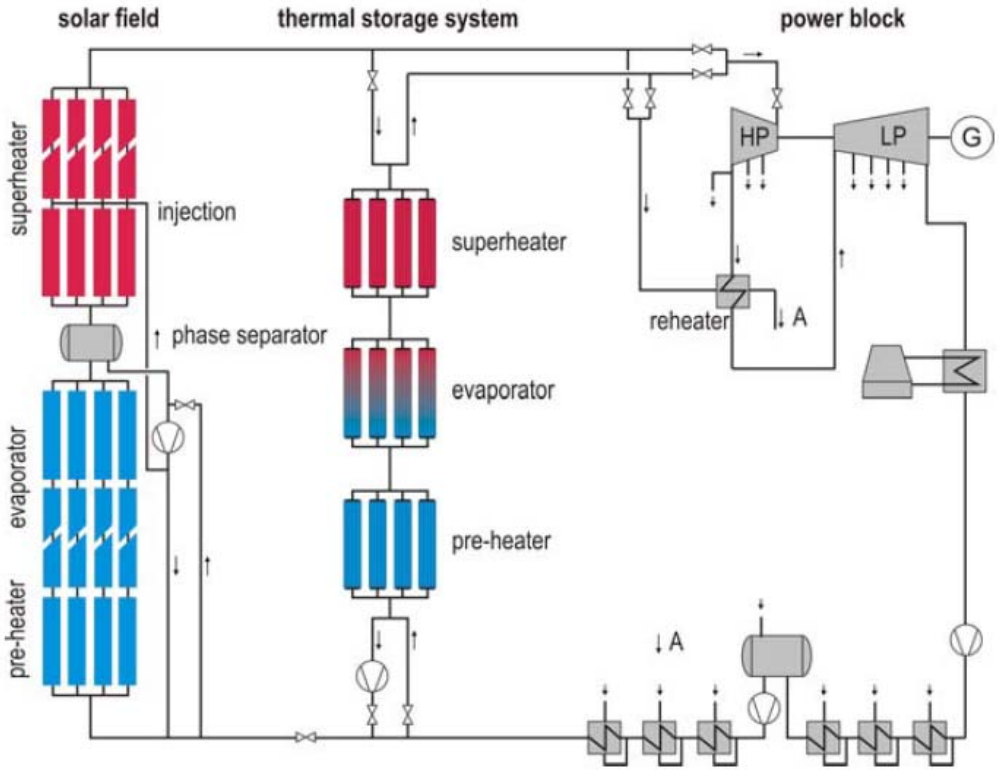
- Outlet temperature can be kept very stable even with easy controllers
- Multiple loops and header piping smooth the temperature significantly
  → no problems in recirculation plants
  → very robust operation in recirculation plants

DSG TES > Upgrading STE Plants

- TES = Thermal Energy Storage

DSG TES > Sytem Overview





Birnbaum, J., Eck, M., Fichtner, M., et al., 2008, "A Direct Steam Generation Solar Power Plant with Integrated Thermal Storage," 14th Bienial SolarPACES Symposium, Las Vegas, USA.

DSG TES > Storage development

Phase change material storage

Phase change material

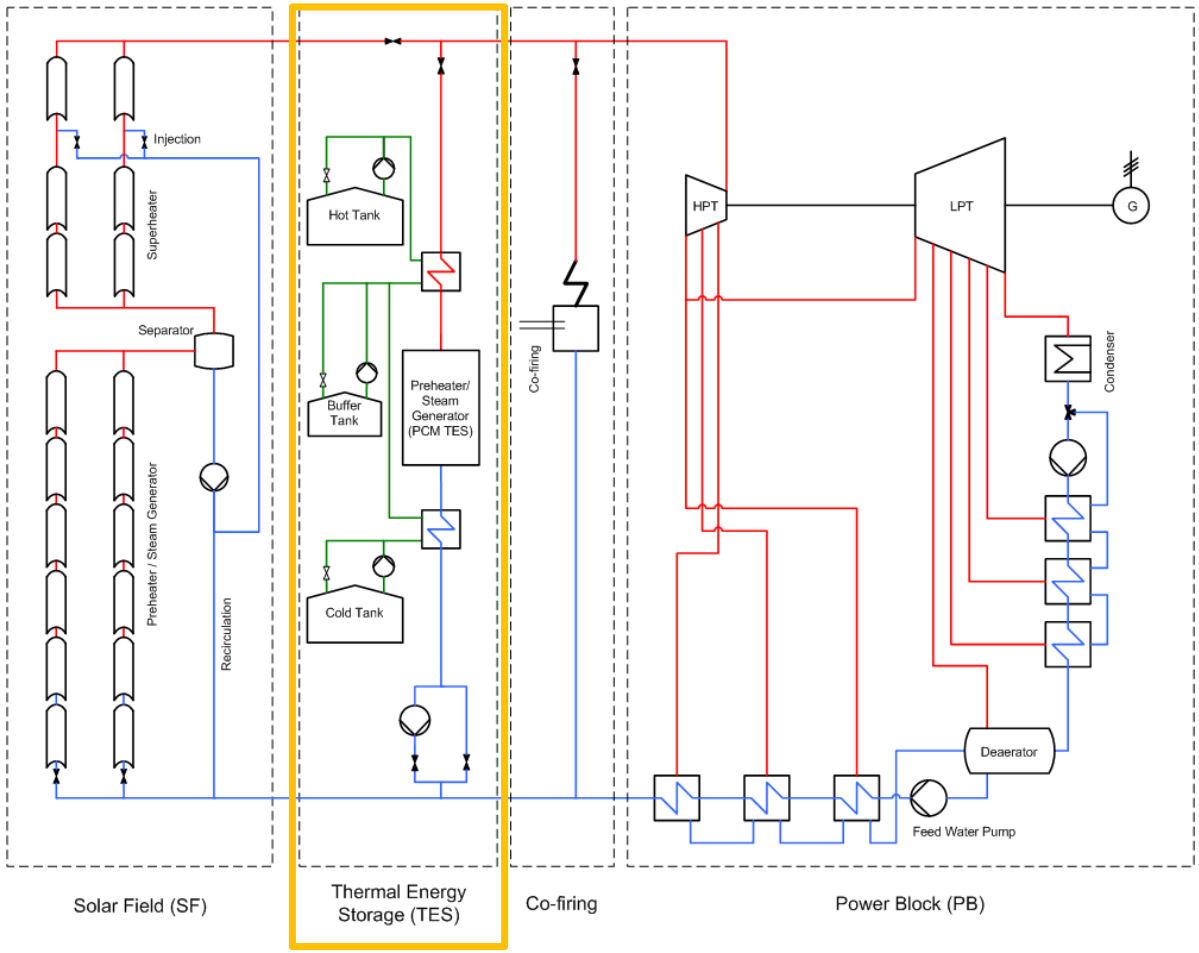
Demonstrated at DLR:

- $NaNO_3$ - KNO_3 - $NaNO_2$ 142 °C
- $LiNO_3$ - $NaNO_3$ 194 °C
- $NaNO_3$ - KNO_3 222 °C
- $NaNO_3$ 306 °C

Experimental validation

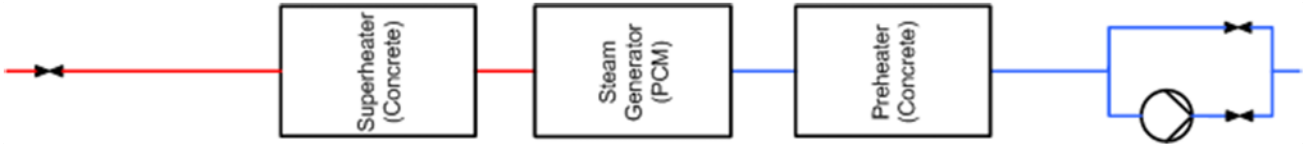
- 5 test modules with 140 – 2000 kg PCM
- Worlds largest high temperature latent heat storage with 14 tons of $NaNO_3$ (700 kWh) operating since 2010

DSG TES > Plant Integration

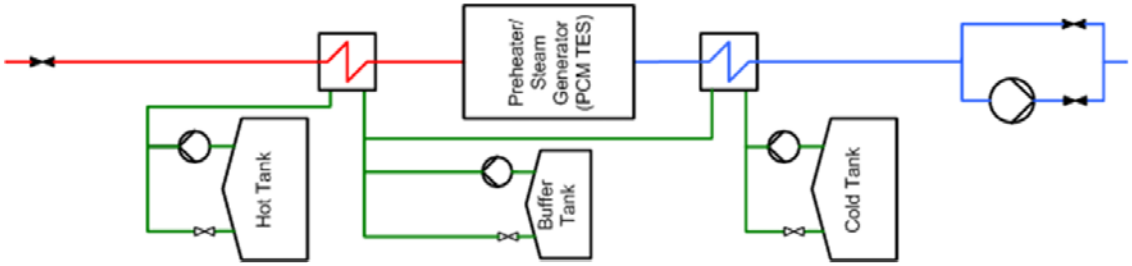


DSG TES > Plant Integration

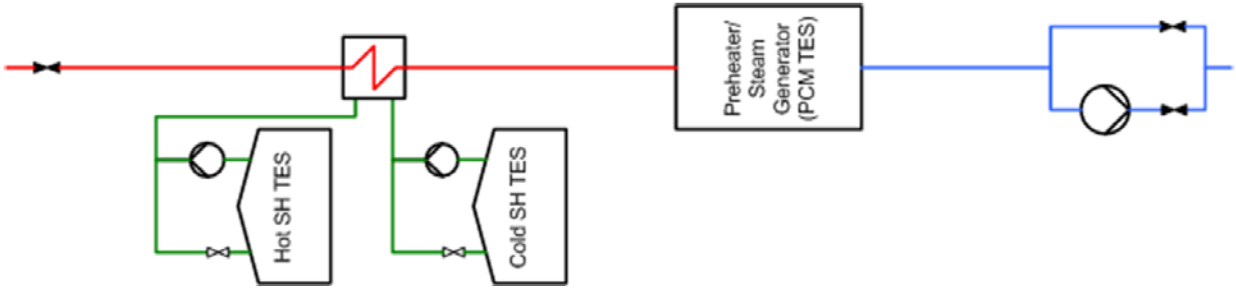
Variant 1:
- PH: Concrete
- SG: PCM
- SH: Concrete



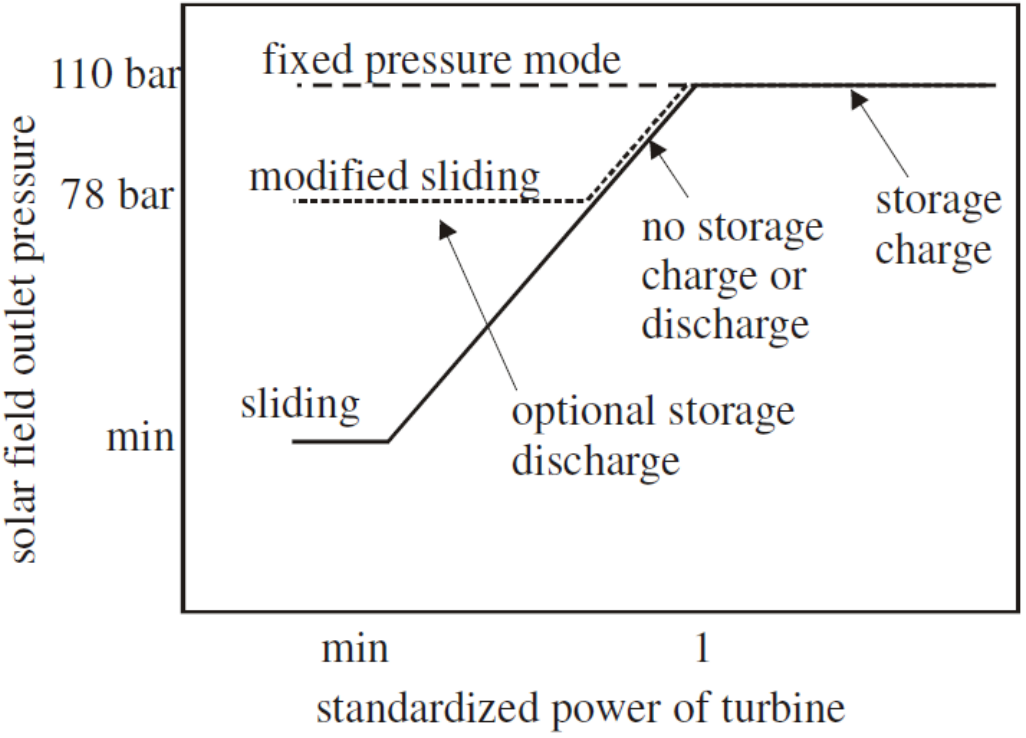
Variant 2:
- PH: Salt
- SG: PCM
- SH: Salt

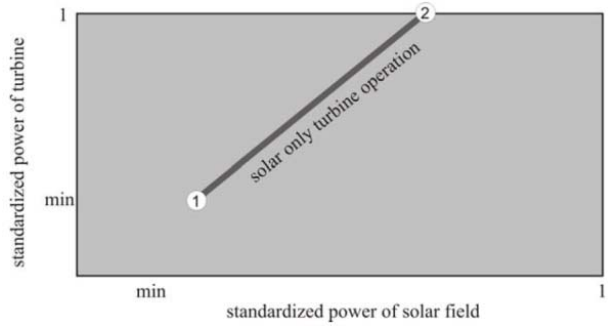


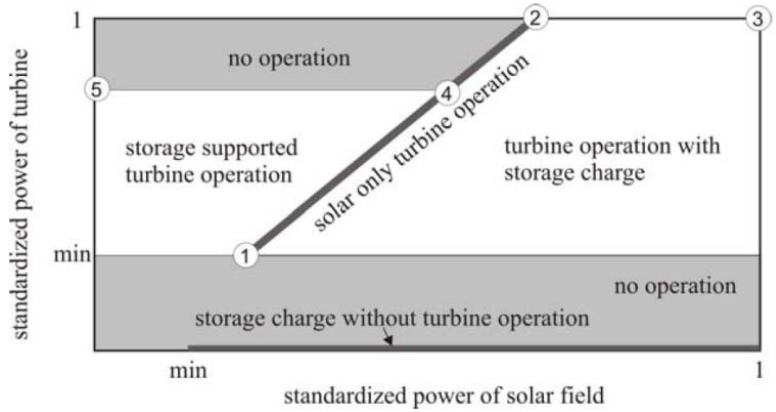
Variant 3:
- PH: PCM
- SG: PCM
- SH: Salt



DSG TES > Power Block Operation







Birnbaum, J., Eck, M., Fichtner, M., et al., 2008, "A Direct Steam Generation Solar Power Plant with Integrated Thermal Storage," 14th Bienial SolarPACES Symposium, Las Vegas, USA.

Outlook and Market > Somebody must build it…

Solarlite: TSE-1

DSG Companies

- Solarlite, Germany
  - Recirculation, trough, superheated steam
- Novatec Solar, Germany
  - Recirculation, Fresnel, saturated steam, probably superheated in future
- Areva Solar, France/Australia
  - Once-through, Fresnel with multiple tubes/counter flow receiver, exact parameters are unknown
- Solar Power Group, Germany
  - Recirculation, Fresnel, no commercial plant realized so far
- Abengoa Solar, Spain
  - Recirculation, trough, superheated steam, only tests at Solucar

Final Remarks on DSG

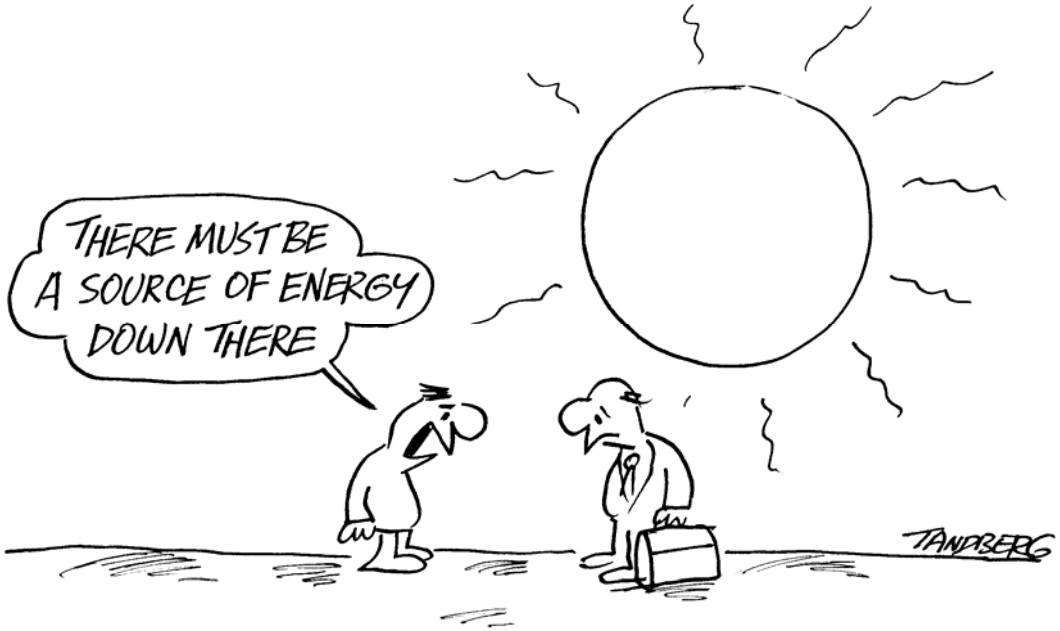
- DSG has reached commercial status!
- For short to mid-term:
  - STE plants without or with small storage
  - Integrated Solar Combined Cycle (ISCC) or fuel saver plants (Don’t use oil for that!)
- For long term DSG perspective:
  - Development of economic PCM storage system
  - Solar field optimization
  - Overall parameter optimization including TES
- There is still a need for research
- There is still a need for a reliable and detailed comparison of alternative STE configurations

Solarlite: TSE-1

Solarlite: TSE-1

Questions and Discussion…

- Contact: jan.feldhoff@dlr.de



By Ron Tandberg

DSG History > Add-on

- An uncomplete list of projects and contents…

DSG activities 1/4

	Duration	Partner	Target
GUDE	1993-96	**DLR**, Siemens, TUM, ZSW	• Thermo-hydraulic effects in horizontal receiver tubes
PRODISS/ ARDISS	1996-99	**DLR**	• Modelling, simulation and control of a collector loop
DISS I/II	1996-2002	CIEMAT, **DLR**, Flagsol, Iberdrola, ZSW, Siemens/KWU	• Planing and erection of DISS plant • Prove of concept • Evaluation of different operation concepts • Validation and improvement of modeling capabilities

DSG activities 2/4

	Duration	Partner	Target
INDITEP	2002-05	CIEMAT, **DLR**, Flagsol, Iberdrola, Siemens, ZSW	• Detailed engineering of a demo loop • Component development (separator, ball-joints, receiver) • Socio-economic analysis
SOLDI	2004-06	**DLR**, (Siemens)	• Evaluation of separation concepts • Process heat generation • Dynamic model library
DISSTOR	2004-07	**DLR**, Züblin, SGL Carbon, CIEMAT, Iberdrola, Flagsol, CNRS, Solucar	• Development, erection and operation of a latent heat storage system

DSG activities 3/4

	Duration	Partner	Target
DIVA	2005-07	SCHOTT, **DLR**, (Flagsol, KK&K)	• Receiver development for 500 °C • Detailed system analysis
ITES	2006-09	**DLR**, Züblin, Siemens	• Planing, erection and operation of a integrated storage system • Optimized control strategies
FRESDEMO	2006-08	MAN, SPG, (**DLR**, FhG-ISE, PSE)	• Planing, erection and operation of a Fresnel collector with DSG • Qualification of the collector

DSG activities 4/4

	Duration	Partner	Target
DETOP	2009-10	**Solar Millennium**, Flagsol, DLR, Schott Solar, Züblin	• Preparation of a demo plant • Detailed system analysis
FRESDEMO 2	2009-13	**Schott Solar**, DLR, Novatec Solar, FhG-ISE	• Optimization of Linear Fresnel Technology and operation
DUKE	2011-14	**DLR**, Solarlite (CIEMAT)	• Extension of DISS plant to 1000 m • Demonstration of once-through operation