Direct Steam Generation (DSG)

Technology Overview

SFERA Summer School 2012
June 28, 2012, Almerá, Spain

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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
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
Parabolic Trough Plants with Oil
Parabolic Trough Plants with Molten Salt
Parabolic Trough Plants with DSG
DSG Advantages and Drawbacks

**Oil**

+ Commercially applied
+ One-phase flow
+ Easily scalable

- Heat exchanger batteries
- $T < 400^\circ C$
- 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!

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

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

Milestones in DSG development
Commercial tower implementations

PS10: 40 bar saturated steam, 11 MWe
PS20: 45 bar saturated steam, 20 MWe

Milestones in DSG development

DSG Component tests at 500 °C

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

Concrete storage system

PCM 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
Milestones in DSG development
Linear Fresnel plants

Kimberlina 5 MWe
106 bar, 400 °C
(higher values announced)
Technology by 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)
Loop Characteristics > Temperature/Steam Quality

![Graph showing temperature and steam quality vs. loop length in number of collectors.](Image)
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 > Temperature profile

- 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

Two-phase flow in horizontal pipes
Pressure loss

![Graph showing pressure loss over length (mbar/m) vs Enthalpy (kJ/kg)]

- Preheating
- Evaporation
- Superheating

Pressure drop DISS plant: Recirculation mode
- Bandel
- Friedel
- Thom

- +35%
- +13%
- +5%
Plant Concepts > How you could run DSG plants
Plant Concepts > Classical approaches

**Recirculation**

Recirculation Mode

**Once-Through (classic)**

Once-Through Mode

**Injection**

Injection Mode

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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

Plant Concepts > Recirculation with central field separators
Plant Concepts > Recirculation with decentral separators

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

Installation and storage space

BOP und Control room

New Solarlite 4600+ collectors (3x 100m)

North
Once-through > Main Changes DISS Solar Field

- New injection instrumentation
- Temperature along end of evaporation and around cross sections
- Relocation of inlet valves
- New balljoints
- New receivers
- New SH injection
- New BOP injection
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

![Graph showing the relationship between main steam temperature and gross power block efficiency for different pressures.]

**Heat Rate [BTU/kWh]**

- 120 bar
- 100 bar
- 60 bar
- 40 bar

**Main Steam Temperature [°C]**

- 350
- 375
- 400
- 425
- 450
- 475
- 500
- 525

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Parameter Optimization > Solar Field (Rec.)

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

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 %

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

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

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

Control > Adaptive Controllers

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


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 > System Overview

DSG TES > Storage development
Phase change material storage

Phase change material
Demonstrated at DLR:
- NaNO3 - KNO3 - NaNO2  142 °C
- LiNO3 - NaNO3  194 °C
- NaNO3 - KNO3  222 °C
- NaNO3  306 °C

Experimental validation
- 5 test modules with 140 – 2000 kg PCM
- Worlds largest high temperature latent heat storage with 14 tons of NaNO3 (700 kWh) operating since 2010
DSG TES > Plant Integration

Solar Field (SF)  

Thermal Energy Storage (TES)  

Co-firing  

Power Block (PB)  

Preheater / Steam Generator  

Hot Tank  

Buffer Tank  

Cold Tank  

Injection  

Separator  

Reboiler  

Preheater / Steam Generator (PCM TES)  

LPT  

Feed Water Pump  

Condenser  

DLR, FF
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

Outlook and Market > Somebody must build it…
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
Questions and Discussion…

- Contact: jan.feldhoff@dlr.de
DSG History > Add-on

- An uncomplete list of projects and contents…
### DSG activities 1/4

<table>
<thead>
<tr>
<th></th>
<th>Duration</th>
<th>Partner</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GUDE</strong></td>
<td>1993-96</td>
<td>DLR, Siemens, TUM, ZSW</td>
<td>• Thermo-hydraulic effects in horizontal receiver tubes</td>
</tr>
<tr>
<td><strong>PRODISS/ARDISS</strong></td>
<td>1996-99</td>
<td>DLR</td>
<td>• Modelling, simulation and control of a collector loop</td>
</tr>
</tbody>
</table>
| **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

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<thead>
<tr>
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</table>
| 2002-05  | CIEMAT, DLR, Flagsol, Iberdrola, Siemens, ZSW | - Detailed engineering of a demo loop  
- Component development (separator, ball-joints, receiver)  
- Socio-economic analysis |
| 2004-06  | DLR, (Siemens) | - Evaluation of separation concepts  
- Process heat generation  
- Dynamic model model library |
| 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

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</table>
| 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

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<th>Partner</th>
<th>Target</th>
</tr>
</thead>
</table>
| 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                                |