Clean Coal Technologies on example of Vattenfall’s Power Plant Projects BOXBERG unit R and MOORBURG

9th Meeting of the Task Force on Regional Energy Cooperation in Central and South Asia (RECA)

7 October 2013, Astana, Kazakhstan

Ronald Rost, Head of Sales & Quality
Vattenfall Europe PowerConsult GmbH, Germany
## Agenda

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The Vattenfall Group
Vattenfall – EU’s fifth largest generator of electricity and the largest producer of heat

Key figures - Vattenfall Group 2012

- Net sales: €20 billion
- Electricity generation: 178.9 TWh
- Heat Sales: 30.3 TWh
- Employees: 32,800
- Electricity customers: 7.4 million
- Local networks: 292,400 km
- Installed capacity: 28,000 MWe

Total Power Generation in %

- Hydro power: 24%
- Nuclear power: 27%
- Fossil based power: 48%
- Wind & other: 3%
<table>
<thead>
<tr>
<th>Plant</th>
<th>Capacity</th>
<th>Commissioned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boxberg</td>
<td>1 x 907 MW</td>
<td>2000</td>
</tr>
<tr>
<td>Schwarze Pumpe</td>
<td>2 x 800 MW</td>
<td>1997 and 1998</td>
</tr>
<tr>
<td>Lippendorf</td>
<td>2 x 933 MW</td>
<td>1999 / 2000</td>
</tr>
</tbody>
</table>

Supercritical Power Plants operated by Vattenfall in Germany
Why Clean Coal Technologies?
Coal Reserves Worldwide

Regional distribution of the worldwide energy reserves for hard coal, lignite, oil, natural gas and uranium/thorium

North America
[287 billion TCE]

Middle and South America
[70 billion TCE]

Europe
(48 billion TCE
EU-27: 38 billion TCE)

Middle East
(245 billion TCE)

Asia, Oceania, Australia
(341 billion TCE)

CIS
(293 billion TCE)

- Oil
- Natural gas
- Uranium/thorium
- Hard coal and lignite

The area of the circles corresponds to the scope of regional energy reserves; the area of the circle segments corresponds to the regional share of each source of energy.

TCE: tonne of coal equivalent
TOE: tonne of oil equivalent
1 TCE ≈ 0.7 TOE

Source: VGB Powertech / BGR 2012

7 | Clean Coal technologies | Ronald Rost | 2013
## Coal's share in electricity generation for selected countries, 2010

<table>
<thead>
<tr>
<th>Country</th>
<th>Hard coal</th>
<th>Lignite</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Africa*</td>
<td>94%</td>
<td></td>
</tr>
<tr>
<td>Poland</td>
<td>57%</td>
<td>31%</td>
</tr>
<tr>
<td>China*</td>
<td></td>
<td>79%</td>
</tr>
<tr>
<td>Australia</td>
<td>53%</td>
<td>23%</td>
</tr>
<tr>
<td>Kazakhstan*</td>
<td></td>
<td>75%</td>
</tr>
<tr>
<td>Serbia*</td>
<td></td>
<td>72%</td>
</tr>
<tr>
<td>India*</td>
<td>67%</td>
<td>2%</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>7%</td>
<td>52%</td>
</tr>
<tr>
<td>Israel</td>
<td></td>
<td>58%</td>
</tr>
<tr>
<td>Taiwan*</td>
<td>50%</td>
<td>5%</td>
</tr>
<tr>
<td>Bulgaria*</td>
<td>14%</td>
<td>36%</td>
</tr>
<tr>
<td>USA</td>
<td>44%</td>
<td>2%</td>
</tr>
<tr>
<td>Greece</td>
<td></td>
<td>45%</td>
</tr>
<tr>
<td>Germany</td>
<td>20%</td>
<td>24%</td>
</tr>
<tr>
<td>World</td>
<td>37%</td>
<td>4%</td>
</tr>
</tbody>
</table>

Source: EURACOAL, A strategy for Clean Coal, 2012
Clean Coal Concept in Germany

Clean Coal I
Retrofit and new build in line with State-of-the-art increase in efficiency, reduction of SO₂, NOx, dust

Source: EURACOAL, Vattenfall
Clean Coal Concept in Germany

Clean Coal I
Retrofit and new build in line with State-of-the-art increase in efficiency, reduction of SO₂, NOx, dust

Source: EURACOAL, Vattenfall
Clean Coal II
R&D for efficiency increase to > 50%

Source: EURACOAL, Vattenfall
Clean Coal Concept in Germany

**Clean Coal III**
CO₂ capture and storage

**Conceptual investigations**

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>Theoretical studies</td>
</tr>
<tr>
<td>2004</td>
<td>Research, Basic principles, Combustion characteristics</td>
</tr>
<tr>
<td>2008</td>
<td>Demonstration of the process chain, Interaction of components, Validation of basic principles and scale-up criteria, Long term characteristics, Non-commercial</td>
</tr>
<tr>
<td>2013 – 2015</td>
<td>Verification and optimization of the component choice, the process and reduction of risks, Must be commercially viable incl. subsidies</td>
</tr>
<tr>
<td>2020</td>
<td>Competitive on the market at that time, No subsidies</td>
</tr>
</tbody>
</table>

Test rig
0.1 – 0.5 MWₑ
< €3 million

Pilot plant
30 MWₑ
€ 70 million

Demonstration plant
300 – 700 MWₑ
> € 1.5 billion

Commercial concept:
~ 1000 MWₑ
Clean Coal Concept in Germany

**Clean Coal IV**
Flexibilisation for complementing renewables

Source: EURACOAL, Vattenfall
Clean Coal Concept

Clean Coal can balance energy security and economic needs with environmental needs

1. Coal is inexpensive, secure and involves no transport risks.
2. Clean coal technologies minimise the environmental impact.
3. Clean coal is the basis for long-term acceptance of coal.

Clean Coal is a flexible concept and can be applied in all countries independently from the specific situation.

Source: EURACOAL, The Long-Term Perspectives for Coal in the EU Electricity Sector, 2007
Snapshot of the German Energy Sector

Increased renewables triggered increased coal based generation
Increasing share of renewables triggers increasing use of coal & lignite

Change of German Power Production from 2011 to 2012

Source: German Energy Agency dena
Electricity Market Price Development (Example)

Market without feed-in of renewables

- Nuclear
- Lignite
- Hard coal
- Natural gas
- Oil

M1: Market price without renewables.

Market with feed-in of renewables at fixed prices for renewables.

- Renewables

M2: Market price with renewables at fixed prices for renewable feed-in.

Capacity bounces from market suffers from reduced operating hours.

Source: VGB Powertech
Wholesale Electricity Price Development

Electricity futures prices

EUR/MWh

NP 13  NP 14  EEX 13  EEX 14  APX 13  APX 14

Jan-10  Apr-10  Jul-10  Oct-10  Jan-11  Apr-11  Jul-11  Oct-11  Jan-12  Apr-12  Jul-12  Oct-12  Jan-13
Lignite- fired Project Boxberg, Unit R

1 x 675 MW
Project Unit R TPP Boxberg (BoxR)

- Base Load Operation
- Availability > 91 %
- Load Range 50 % to 103 %
- High Control Level
- Compliance with Transmission Code
- LHV Net Efficiency > 43.7 %
  (Live Steam: \( t = 600 ^\circ \text{C}; \ p = 285 \text{ bar} \))
- Coal Consumption: 4.5 Mio. t/a
- Land requirem.: 100,000 m²
- Specific CO2-Emissions: 924 g/kWh
### Development of efficiency of lignite power plants

<table>
<thead>
<tr>
<th>Location</th>
<th>Temperature</th>
<th>Pressure</th>
<th>Carnot Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jänschwalde TPS</td>
<td>554 °C</td>
<td>267 bar</td>
<td>43.7</td>
</tr>
<tr>
<td>Schwarze Pumpe TPS</td>
<td>583 °C</td>
<td>270 bar</td>
<td>44.1</td>
</tr>
<tr>
<td>Lippendorf TPS</td>
<td>580 °C</td>
<td>285 bar</td>
<td>44.8</td>
</tr>
<tr>
<td>Unit R</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jänschwalde TPS</td>
<td>535 °C</td>
<td>169 bar</td>
<td>43.7</td>
</tr>
<tr>
<td>Schwarze Pumpe TPS</td>
<td>540 °C</td>
<td></td>
<td>44.1</td>
</tr>
<tr>
<td>Lippendorf TPS</td>
<td>590 °C</td>
<td></td>
<td>44.8</td>
</tr>
</tbody>
</table>

### Notes
- **10CrMo 9.10**
- **P91**
- **P92**
- **Ni-Basis-Alloy**
- **Integrated drying**
- **Carnot Efficiency**
Main Equipment BoxR

**Turbine Hall**
- Turbine: ALSTOM
- 4 casings
- Single reheater
- 2 condensers in sequence
- 9 pre-heaters

**Boiler**
- HPE
- Benson-boiler
- Round coal burners
- Single line air and FG system
- Complex diagnostic systems

**ESP**
- ELWO
- RAFAKO
- Horizontal ESP
- Newest generation of voltage control
- HV-aggregates on the roof

**ID fan**
- HPE

**FGD Plant**
- Babcock-Noell
- Open air placement
- Washer protected by rubber
- Installation of tray below spray levels

**CT with FG inlet**
- Hamon
- Natural ventilation
- High efficiency equipment
- Possible operation of sections
- Single FG-inlet, channel-Ø 7,5 m

+ 135 m

+ 155 m
BoxR- Boiler Features

High pressure part

Steem rating: 1760 t/h
Allowable working pressure (gauge): 315 bar
SH-Outlet temperature: 600 °C

Reheater

Allowable working pressure (gauge): 72 bar
RH-Outlet temperature: 610 °C
Year of commissioning: 2011
BoxR – Turbine and Flue Gas Cleaning

Turbine and Generator, Machine house +15 m

Electrostatic precipitator and flue gas desulphurisation plant
<table>
<thead>
<tr>
<th>Year</th>
<th>Site Field</th>
<th>Excavated</th>
<th>Cooling Tower (M/s Heitkamp)</th>
<th>Cooling Water Pipelines (M/s Porr)</th>
<th>Foundation (M/s Strabag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>ca. 100.000 m²</td>
<td>ca. 260.000 m³</td>
<td>Bottom Diameter: 100 m</td>
<td>Diameter: 3.60 m</td>
<td>Turbine Hall: 89 x 51 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Height: 155 m</td>
<td>Length: ca. 600 m</td>
<td>Boiler Hall: 88 x 84 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Switchgear B.: 18 x 51 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>max. thickness: 3.80 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Concrete: ca. 40.000 m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Reinforcement: ca. 10.500 t</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Height of Boiler Hall: 135 m</td>
</tr>
</tbody>
</table>
Start of boiler erection works
Placing of feed water tank
Delivery of turbine condensers
Arrival of generator stator at site
Installation of evaporator panels
Test of transformer’s water spray system
First oil fire on 20.09.10
First coal fire on 08.10.10

Stop of commissioning on 20.10.10 because of boiler leakages
BoxR- Location of Defects on Boiler

Defects on Evaporator
- Area from +55m to +65m (last section of evaporator as part of the membrane wall)

Activities
- Comprehensive inspections and assessment of defects till February 2011
- Conservation of plant during the break time of commissioning activities
- Investigation of two different technical solutions in parallel:
  * repair of the damaged part of evaporator
  * replacement of the damaged part of evaporator
- Decision was made in April 2011 to replace the damaged parts of evaporator
BoxR - Boiler – Replacement of evaporator panels

Boiler front wall after replacement of T 24 parts of evaporator (09.11.2011)

880 m²
9,218 weld seams
BoxR – Change of T 24 material at evaporator

Inner scaffolding for material change at evaporator (10.02.2011)

Transport change panel (15.09.2011)
BoxR - Boiler – Flushing and Heat Treatment of SH 1

Flushig

Provisional flue gas exhaust on boiler house roof during heat treatment process (28.11.2011)

Compressors for air injection during high velocity flushing and for temperature control during heat treatment of superheater 1 (25.11.2011)

Heat treatment

Protection layer establishment
First synchronisation of Boxberg R in February 2012

Start of commercial operation on 09.10.2012
Hard Coal-fired Project Moorburg, Unit A + B

2 x 820 MW
Moorburg site with decommissioned 2x 500 MW
Moorburg TPS - Aerial view

3D Model as of October 2011 including hybrid cooling tower
### Moorburg Power Plant, Technical Data

- **Electrical gross capacity:** $2 \times 820 \text{ MW}_{el}$
- **District heat extraction:** $450 \ (600) \ \text{MW}_{th}$
- **Net Efficiency (condensing mode):** ca. 46.5%
- **Fuel utilisation (with full district heating):** ca. 60%
- **Live steam pressure:** 276 bar
- **Live steam temperature:** 600°C
- **Reheat steam temperature:** 620°C
- **Coal consumption (worldwide imports):** ca. 3.5 mio. t/a
- **Load change:** 40 - 103 %
- **Operation hours per year (design):** > 7,500 h/a
Emission limit values of Moorburg

**Permitted Stack Emission Limit Values (ELV)**

ELV based on 6\%O₂ and 0 °C und 101.3 kPa ambient conditions

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Dimension</th>
<th>Emission Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Daily average</td>
</tr>
<tr>
<td>Particulate matter</td>
<td>mg/m³</td>
<td>10</td>
</tr>
<tr>
<td>Mercury</td>
<td>mg/m³</td>
<td>0.03</td>
</tr>
<tr>
<td>CO</td>
<td>mg/m³</td>
<td>100</td>
</tr>
<tr>
<td>Nitrogen oxides as NO₂</td>
<td>mg/m³</td>
<td>70</td>
</tr>
<tr>
<td>Sulphur oxides as SO₂</td>
<td>mg/m³</td>
<td>100</td>
</tr>
<tr>
<td>Dioxins and Furane</td>
<td>ng/m³</td>
<td>0.01</td>
</tr>
<tr>
<td>Ammonia</td>
<td>mg/m³</td>
<td>5</td>
</tr>
</tbody>
</table>
Energy Efficiency Measures and comparison with Best Available technology (BAT)
Net Efficiency and Fuel utilisation (incl. DH) of built and planned hard coal power plants in Germany

- **Rostock TPS**: 553 MW (1994)
  - Net Efficiency: 545 °C, 562 °C, 260 bar, 53.2%
  - Fuel Utilisation: 45%

- **Walsum TPS**: 750 MW
  - Net Efficiency: 600 °C, 610 °C, 276 bar, 53%
  - Fuel Utilisation: 45%

- **Moorburg TPS**: 2 * 820 MW
  - Net Efficiency: 600 °C, 610 °C, 276 bar, 57%
  - Fuel Utilisation: 46%
## Comparison of Moorburg and Rostock TPS

<table>
<thead>
<tr>
<th>Year of commissioning</th>
<th>Rating el. Net Efficiency (LHV)</th>
<th>TPS Rostock 1994</th>
<th>TPS Moorburg 2011</th>
<th>Efficiency increase [per cent points] Σ + 3.4 %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 x 500 MW 43.1 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 x 827 MW 46.5 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live steam</td>
<td>545°C, 262 bar</td>
<td>600°C, 287 bar</td>
<td></td>
<td>+ 1.40%</td>
</tr>
<tr>
<td>Reheat steam</td>
<td>562°C</td>
<td>610°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>regenerative pre-heater stages</td>
<td>7</td>
<td>9</td>
<td></td>
<td>+ 0.30%</td>
</tr>
<tr>
<td>Cooling water temperature</td>
<td>Cooling tower</td>
<td>River water</td>
<td></td>
<td>+ 0.60%</td>
</tr>
<tr>
<td>Reduced own consumption of the power plant</td>
<td>i.e. use of controlled drives, optimised components</td>
<td></td>
<td></td>
<td>+ 0.90%</td>
</tr>
<tr>
<td>Improved waste heat utilisation</td>
<td>Pulveriser heat exchanger</td>
<td></td>
<td></td>
<td>+ 0.20%</td>
</tr>
</tbody>
</table>
## Comparison of TPS Moorburg with BAT

<table>
<thead>
<tr>
<th>Process step</th>
<th>Parameter BAT</th>
<th>Parameter Moorburg</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler efficiency</td>
<td>95 % for hard coal</td>
<td>95,38 %</td>
<td>After cleaning / inspection</td>
</tr>
<tr>
<td>Stochiometric air ratio</td>
<td>1.15 – 1.25</td>
<td>1.16</td>
<td></td>
</tr>
<tr>
<td>Steam after RH</td>
<td>300 bar, 600 °C</td>
<td>276 bar, 600 °C LS 50.9 bar 610 °C HRH</td>
<td>The process of district heat extraction was optimised and therefore does not fully reach the parameters of a high-end condensation power plant.</td>
</tr>
<tr>
<td>Turbine efficiency</td>
<td>91 bis 96 %</td>
<td>HP-part 92.87% MP-LP-parts 92.63%</td>
<td></td>
</tr>
<tr>
<td>Preheater stages</td>
<td>Up to 10</td>
<td>9 + 1 separate desuperheater stage</td>
<td></td>
</tr>
<tr>
<td>Feedwater temperature</td>
<td>300 °C</td>
<td>293.4 °C</td>
<td></td>
</tr>
<tr>
<td>Condenser pressure</td>
<td>&lt; 30 mbar (abs)</td>
<td>25 mbar (abs)</td>
<td></td>
</tr>
</tbody>
</table>
# Comparison of TPS Moorburg with BAT

<table>
<thead>
<tr>
<th>Process step</th>
<th>Parameter BAT</th>
<th>Parameter Moorburg</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue gas discharge</td>
<td>70 - 80 °C</td>
<td>$T_{\text{flue gas}} &lt; 60 , ^\circ \text{C}$</td>
<td>Wet stack without reheating of flue gases</td>
</tr>
<tr>
<td>SCR-Catalyst</td>
<td>High-Dust mode</td>
<td>High-Dust mode</td>
<td></td>
</tr>
<tr>
<td>Electr. own consumption</td>
<td>Optimisation of auxilliary and ancilliary systems</td>
<td>Optimised pumps, fans, ID fan etc. with energy efficient controls</td>
<td>Speed control, blade pitch</td>
</tr>
<tr>
<td>Net Efficiency (LHV)</td>
<td>45 %</td>
<td>46.5 %</td>
<td>Plant optimisation was based on District Heating Extraction</td>
</tr>
</tbody>
</table>
Comparison of TPS Moorburg ELVs with EU IED

Emission Limit Values Comparison

- SO2
- NOx
- Dust
- CO
- NH3
- Hg

IED mg/Nm³
German LCP mg/Nm³
Moorburg TPS mg/Nm³
CCS development for reducing CO$_2$
The idea is to capture carbon dioxide from a coal-fired power plant, compress (liquify) it and permanently store it deep underground.

The storages are of the same kind of structures that oil and gas are extracted from - a porous rock with a sealing cap on top or saline aquifers.
CO₂ Reduction Potential by Efficiency Increase and CCS

CO₂ reduction potential of coal-fired power plants by increased efficiency

- Average worldwide
  - 33%: 1,015 g CO₂/kWh, 436 g coal/kWh
  - 38%: 881 g CO₂/kWh, 379 g coal/kWh

- EU
  - 45%: 743 g CO₂/kWh, 320 g coal/kWh

State of the art
- Steam power plant 700 °C technology
  - About 50%: 669 g CO₂/kWh, 288 g coal/kWh

CCS technology
- But: Efficiency loss of 7 to 12% points
  - -90%

Source: VGB Powertech
Economic Driver for CCS

Electricity generation costs (assuming 30 €/ton CO₂)

€/MWh

- Large PF plant
- ETS cost
- PF plant CCS
- ETS cost

CO₂ cost
Fuel
O&M
Capital
Market driver

EU CO₂ price development 2010 – 2013

Source: Vattenfall AOT
CCS Technologies for a low CO$_2$ Power Plant
Post-Combustion Capture Process

Post-combustion capture (absorption process)

New plant equipment with regard to conventional power generation.
Oxyfuel Process

New plant equipment with regard to conventional power generation.
Pre-Combustion (IGCC) Process

Pre-combustion decarbonisation capture

New plant equipment with regard to conventional power generation.
**Potential of CCS Technologies**

**Post-Combustion-Capture**
This chemical scrubbing process is best suited for retrofit of existing plants. It is most developed, but comes with the largest efficiency penalty.

**Oxyfuel**
Oxyfuel is best suited for new build plants. It offers the lowest efficiency penalty.

**Pre-Combustion-Capture**
IGCC with CO$_2$ capture offers great potential for the material use of coal (precursor for chemical industry). Has a similar efficiency penalty as oxyfuel.
Vattenfall’s CCS projects

Vattenfall CCS project progress

- **2001** Start of Vattenfall’s CCS project
- **2002 – 2004** Test-rigs at five European universities operation
- **2005** Investment decision for the Oxyfuel pilot plant
- **2006** Groundbreaking ceremony for the pilot plant in Schwarze Pumpe
- **2008** Oxyfuel pilot plant in Schwarze Pumpe in operation
- **2008** Seismic surveys in Nordjylland initiated
- **2009** CO₂ injection in Altmark starts
- **2009** CCS demo in Jänschwalde in operation
- **2013** CCS Demo at Nordjyllandvaerket in operation
- **2020** CCS technology commercially available
Vattenfall’s Schwarze Pumpe Oxyfuel Pilot Plant

Inaugurated in September 2008

First test period from 2008 – 2011, combustion with lignite
Second test period with bituminous coal 2012 - 2014

Operational hours total 12,700 (08/2008 – 04/2011
   Hours (air operation) 3,750
   Hours (oxyfuel operation) 9,850

Captured CO₂ 6,890 t
Capture rate > 90 %
CO₂-purity > 99.7 %
Jaenschwalde Oxyfuel & Post-Combustion Demo Plant

- Both Oxyfuel and Postcombustion technologies will be investigated
- Jaenschwalde today consists of 6 units of 2 boilers and a 500 MWe turbo-generator each
- Fired with lignite from an open cast mine near by
- “Double-demo” when Block F is both retrofitted with Post-combustion and a new Oxyfuel boiler is added
- Possible options for CO₂ storage are under investigation
Vattenfall’s Pre-Combustion Pilot Plant IGCC Buggenum

CO₂ Catch-up pilot plant at Buggenum

Objective: Testing pre-combustion CO₂ capture technology at IGCC
- Identify and mitigate potential risks associated with the novel application of the selected technology
- Verify the technology performance and operation window in the field environment
- Optimize technology selection and design
- Gather operating experience
- Prepare for large-scale application in Magnum

Main features
- 3 sweet WGS reactors, physical CO₂ absorption
- CO₂ capture 10 kt/yr
- > 40 M€ total investment + R&D programme
- Commissioning Q3 2010
- Test programme of min. 1.5 year
Большое спасибо за внимание!
Many Thanks for your Attention!
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