An Overview of CO₂ Capture Technologies
What are the Challenges Ahead?

by:
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IEA Greenhouse Gas R&D Programme

Presented at:
Workshop on Capture and Sequestration of CO₂ (CCS)
10th July 2008
Mexico City

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http://www.ieagreen.org.uk
Presentation Outline

- IEA Greenhouse Gas R&D Programme
- Briefly summarise international policy developments and regulatory developments
- Overview of CO$_2$ capture technologies for power generation
  - Post-Combustion Capture
  - Oxy-Combustion Capture
  - Pre-Combustion Capture
- What challenges, issues and future development in the three leading CO$_2$ capture technologies.

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Brief Introduction to

IEA Greenhouse Gas R&D Programme (IEAGHG)
IEA Greenhouse Gas R&D Programme

- A collaborative research programme founded in 1991
- Aim is to:
  
  *Provide members with definitive information on the role that technology can play in reducing greenhouse gas emissions.*

- Funding approximately 2.5 million $/year.
- Activities:- Studies (>100), international research networks, facilitating and focussing R&D and demonstration activities
- Producing information that is:
  - Objective, trustworthy, independent
  - Policy relevant but NOT policy prescriptive
  - Reviewed by external Expert Reviewers
  - Subject to review of policy implications by Members

http://www.ieagreen.org.uk
IEA GHG is one of 40 organisations having an implementing agreement with IEA.

http://www.ieagreen.org.uk
Technology and Market Information

Implementation Support
- Methodology for CCS projects under CDM
- Guidelines for CCS site characterisation
- CCS Project Financing
- Regional capacity for CO₂ storage in India

Technical Assessments
- Improved solvent scrubbing processes for CO₂ capture
- Capture of CO₂ from medium scale installations
- Improved Oxygen production processes
- Collection of CO₂ from distributed sources
- CO₂ Capture in the cement industry
- Co-production of hydrogen and electricity
- Remediation of leakage from geological storage
- Fuel Cells for CHP
- CO₂ Pipeline transmission costs

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IEA Greenhouse Gas R&D Programme

- Provide a forum for Governments and Industry to cooperate
- Collaborate with other international bodies
  - International Energy Agency & G8
  - CSLF and APEC

http://www.ieagreen.org.uk

GHGT-9
16th – 19th November 2008
Washington D.C.
http://mit.edu/ghgt9
Development of CCS
(Brief summary of International Policy Development)
International Policy Developments

• International acceptance of CCS was seen as a major barrier to CCS deployment 2/3 years ago
  o Situation has changed significantly in previous year
  o Main International Environmental Treaty is the Kyoto Protocol
    ▪ CCS accepted as a mitigation option in 2007
  o Remaining Barrier: Acceptance of CCS to be included in CDM
    ▪ Awaiting decision under COP/MOP4 meeting in Poland (Dec. 2008)

• Key International Marine Treaties (i.e. London Convention / OSPAR) adopted amendments to allow CCS in sub sea geological structures
  o Established guidelines for risk assessment and management for \( \text{CO}_2 \) storage in sub sea geological structures

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Role of CCS in climate change mitigation?

- IEA Technology Perspectives (2006) – CCS 20-28% of mitigation to 2050. Second only to energy efficiency.
- Stern Report (2006) – CCS ~10% mitigation by 2025, ~20% by 2050. Marginal mitigation costs without CCS increase by ~60%.
- EC/Shell (2007) - 7 yrs delay CCS = 90GT CO2 to 2050 = 3 yrs global emissions = 10ppm
- World Energy Outlook 2007. “CCS is one of the most promising routes for mitigating emissions in the longer term and could reconcile continued coal burning with the need to cut emissions in the longer term”.

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## Regulatory Developments

<table>
<thead>
<tr>
<th>Country/Region</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>EC Draft Directive on CCS developed – focuses on regulatory development for storage component. Other areas (transport, capture) covered by existing regulations</td>
</tr>
<tr>
<td>USA</td>
<td>IOGCC drafted guidelines for CO₂ storage in geological formations where states have primacy. USEPA drafting overarching state guidance for CO₂ storage. CO₂-EOR already covered by existing state and federal laws. USDOT regulations cover transport of CO₂.</td>
</tr>
<tr>
<td>Canada</td>
<td>New GHG emissions legislation being drafted will include a CCS provision. Provinces already regulate CO₂ transport, CO₂-EOR and acid gas disposal.</td>
</tr>
<tr>
<td>Australia</td>
<td>Federal Government to redraft oil and gas legislation to accommodate CCS. State of Victoria has a consultation document for CCS.</td>
</tr>
</tbody>
</table>
General Overview of CO$_2$ Capture
Current View on CCS and Efficiency Increase

- Key issue will be value of CO₂
- Zero Emissions Trajectory
- Increased Efficiency Trajectory

CCS will need the most efficient plant
The three options

Post Combustion
Decarbonisation

Precombustion
Decarbonisation

Oxy firing

Fossil Fuel

CO₂ Compression & Dehydration

- Enhanced Oil Recovery
- Enhanced Coal Bed Methane
- Old Oil/Gas Fields
- Saline Formations

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Post-Combustion Capture
Post-Combustion Capture

Power generation

Air
Fuel
Steam

Boiler or gas turbine

Steam turbine

(FGD/SCR)

Solvent scrubbing

CO₂ compression

Capture

N₂, O₂, H₂O to atmosphere

CO₂ to storage

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Chemical Absorption Process
Post-Combustion CO₂ Capture
(Typical Operating Parameters)

• For MEA (with 30% solution) operation:
  
  o Absorber: CO₂ removal
    (40-60°C)
  
  o Regenerator (Stripper): CO₂ release & solvent regeneration
    (100-120 °C)
  
  o Efficiency: Up to 95+% CO₂ removal from flue gas
  
  o CO₂ product: 99+% CO₂
    (capability to achieve food grade CO₂)
  
  o Energy requirements: Sourced from the steam from turbine
Post-Combustion CO$_2$ Capture
(Bellingham, MA, USA)

- 350 TPD Liquid CO$_2$ Plant using Econamine FG SM* (proprietary MEA based solvent)
- CO$_2$ is captured from the flue gas of a gas turbine (a cogen facility) having 14% O$_2$ in the flue gas.
- Operated by the Suez Energy Generation

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CO$_2$ Based Solvent Scrubbing

- Use of Amine scrubbing to capture CO$_2$ is the most mature among the 3 mostly considered capture technology options for the power generation.
- Amine based solvent is currently the commonly used for CO$_2$ capture
  - widely used in food processing (ie. carbonated drinks) and chemical industries (ie. Urea plant)
  - Many large scale storage demonstration (> 1 MT/yr of scale) – mostly in oil and gas fields applications (For example in Sleipner, Salah and Snohvit)
- Current R&D Focus
  - Improvement to current solvent
  - Development on column design and packing
  - Development for scaling up (from < 1000 TPD to ~5000 TPD per unit)
  - Development of new type of solvents
  - Development is also on-going for application to coal fired power plant
**MITSUBISHI CO₂ Recovery Technology from Flue Gas**

**<Experience and R&D Facilities>**

### MHI’s Evolution Development of Flue Gas CO₂ Recovery Plant

<table>
<thead>
<tr>
<th>Evolution</th>
<th>91</th>
<th>92</th>
<th>93</th>
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<td>• Japan, Chemical Company (330 Tonnes/day)</td>
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<td>• India, Fertilizer Company (450 Tonnes/day x 2)</td>
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<td>• Abu Dhabi, Fertilizer Company (400 Tonnes/day)</td>
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</table>

-1 Ton/Day Pilot Test Completed
-Long Term Demo. Plant
-Test Starts
-Large Scale Demonstration
-Plant Design Ready

-1 Ton/Day
-Pilot Test Completed
-Long Term Demo. Plant
-Test Starts
-Large Scale Demonstration
-Plant Design Ready

-3000 Tonnes/Day Plant Design Completed
-6000 Tonnes/Day Plant Design Completed
-FGD Experience

-Commercial Plant
-Malaysia Kedah Plant
-330 Tonnes/day Plant

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MITSUBISHI HEAVY INDUSTRIES, LTD.
Post-combustion capture: KEY ISSUES

• Solvent life
  ○ Requires very low SOx (< 10 ppm) and NO$_2$ (< 20 ppm)
  ○ Solvent could be very expensive – target: lower solvent losses

• Corrosion
  ○ Stainless steel v carbon steel
  ○ Inhibitors can contain V, Sn, Sb (antimony)

• Energy consumption
  ○ Regeneration of solvent

• Environmental impacts
  ○ Some degradation products known and regulated; others are not.
Future Direction of Research

• Cost and Process Optimisation of the current MEA based Technologies
  ○ Design of the Absorption column
  ○ Reduction of Energy consumption of the regenerative column
• Improvement of Current solvents
  ○ Improving kinetics
  ○ Improving additives to reduce degradation
• Development of new solvents
  ○ For Examples: Chilled Ammonia process, Cansolv solvent, KS2, etc...
• Environmental Impact Assessment
  ○ Impact assessment due solvent degradation
  ○ Fugitive emissions (especially NH3 as one of the by-product of degradation)
R&D Effort in Europe

- Castor Post-Combustion Pilot Plant Project
  - Installed at the Esbjerg Power Station
- Pilot Capacity: 1000 kg CO₂ per hour (25 TPD)
- 5000 Nm³/h flue gas (coal combustion)
- Now in operation
  - started in March 2006
  - CASTOR programme is now complete. Work will be continued in CEASAR Project
On February 6, 2008 Vattenfall Nordic Thermal Power Generation announced the intention to develop a full-scale Carbon Capture & Storage (CCS) demonstration project.
Other Developments

• Development in new novel solvent
  o CANSOLV Process
  o Alstom Chilled Ammonia Process
  o Powerspan ECO₂ Ammonia process

• Other Large Scale Demonstration Project
  o UK BERR Competition (currently 4 consortium shortlisted)
  o Germany - Vattenfall’s Janschwalde Project

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Oxy Fuel Combustion with CO$_2$ Capture
Oxy-Coal Combustion with CO$_2$ Capture

Oxygen from air separation is fed into the boiler along with fuel. The boiler produces steam, which is used in the steam turbine to generate power. Recycled flue gas is also fed into the boiler. The CO$_2$ emissions are captured and compressed for eventual venting or storage.
Prior to any retrofit of carbon capture technology, it is essential to repower the plant in order to achieve the highest possible efficiency.
Oxy-Combustion Technology

- Use of oxygen instead of air in a boiler – “Oxy-Combustion” is the least mature among the 3 mostly considered capture technology options for the power generation.
- 3 key development issues
  - Boiler and burner development
  - Air Separation Unit – “Cost and capacity of oxygen production”
  - CO$_2$ processing – “Removal of impurities”
ANL - EERC Study
World’s 1st Oxy-Coal Pilot Scale Study
Tower Furnace (~ 3MWth)

http://www.ieagreen.org.uk
Coal Flame Photos: Air Fired vs Oxy-Fired (Courtesy of IHI)

- Air mode ($O_2 : 21\%$)
- Oxy mode ($O_2 : 21\%$)
- Oxy mode ($O_2 : 30\%$)

http://www.ieagreen.org
- Recycle Ratio = 0.58

- O₂-RFG flame with recycle ratio = 0.58

- Recycle Ratio = 0.61

(~ 0.61 include the CO₂ to transport coal)

- Recycle Ratio = 0.76

- O₂-RFG flame with recycle ratio = 0.76

- Recycle Ratio = 0.76

- Courtesy of IFRF
1st Large Scale Oxy-Coal Combustion Experience (International Combustion Ltd.)

- 35 MWth Low NOx burner
- Although it was not able to achieve the desirable CO₂ composition – the first combustion trial gained significant experience in burner start up
Oxy-Combustion Technology

What are the Enabling Studies in the near future that will provide a big step forward for Oxy-Coal Combustion...
Vattenfall Schwarze Pumpe Pilot Project

- Time Table for Implementation of Oxy-Fuel Project

<table>
<thead>
<tr>
<th>Year</th>
<th>Pre- and Order planning</th>
<th>Permission planning</th>
<th>Execution planning</th>
<th>Erection</th>
<th>Commissioning</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>2006</td>
<td>2007</td>
<td>2008</td>
<td>2009</td>
<td>2010</td>
<td>2011</td>
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</tbody>
</table>

- Courtesy of Vattenfall
Schwarze Pumpe Oxy-Combustion Pilot Plant

Courtesy of Vattenfall AB
What it looks like today...
Callide A Project:
Japanese-Australian Collaboration

Figure 2: Location of Callide-A Project. A Planned retrofit to a coal fired power plant with an oxy-combustion boiler
Doosan Babcock Burner Test (2008/09)

- Pilot scale tests by Mitsui Babcock 1994
- IEA, EU projects underway
- EON 1MW rig recently announced
- Vattenfall 30MW demonstration plant announced
- Several boiler makers developing this technology for 2010/12 implementation
- Full scale 60MW burner test planned by MBEL in 2007/8
- DTI funded collaborative R&D projects in preparation

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Oxy-Combustion: KEY ISSUES

- **Air Ingress**
  - Estimated that every 1% of air ingress should be equivalent to about 4% reduction of the CO₂ concentration in the flue gas.
  - Several failures have been noted from previous experiences of not reaching the desired concentration of CO₂ due to air ingress.
  - This is a big challenge especially retrofitting a power plant.

- **Boiler and Burner Development**
  - We need to build our confidence in running an oxy-fired burner/boiler especially at the same scale of our current PC boiler.
  - Various technical issues elucidated - these include heat transfer aspect, ash and slagging, equipment scaling up, etc…
  - Largest burner test as of today operated with oxy-firing mode for coal was done by International Combustion during the 1990’s - what have we learned from this test?

- **Cost and capacity of producing your oxygen**
- **CO₂ purity will be a very sensitive issue to this technology - this would have significant impact to economics of the plant**
Oxy-Combustion: KEY ISSUES

- SO$_3$ issue is a big missing link!
- ANL study (1985) have indicated that SO$_3$ formation is 3 to 4 times greater as compared to conventional air – firing mode
- We need to know more about this potential operational issue.

- From Chemical Engineering Progress (Vol. 70)
• Measured SO$_3$ concentrations for Lausitz coal at AIR and OXYFUEL combustion conditions

<table>
<thead>
<tr>
<th></th>
<th>SO$_2$ measured, ppm</th>
<th>SO$_3$ measured, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>733</td>
<td>8 (6 – 11)*</td>
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<tr>
<td>OXYFUEL</td>
<td>1758</td>
<td>85 (36 – 121)*</td>
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*... min. / max. value measured
### Large Scale Pilot and Demo Projects

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>Location</th>
<th>MWt</th>
<th>Start up</th>
<th>Boiler Type</th>
<th>Main Fuel</th>
<th>CO2 Train</th>
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<tbody>
<tr>
<td>B &amp; W</td>
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<td>Bit, Sub B., Lig.</td>
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<td>2008</td>
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<td>Vattenfall</td>
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<td>30</td>
<td>2008</td>
<td>Pilot PC</td>
<td>Lignite (Bit.)</td>
<td>With CCS</td>
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<tr>
<td>Total, Lacq</td>
<td>France</td>
<td>30</td>
<td>2009</td>
<td>Industrial</td>
<td>Nat gas</td>
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<td>Bit.</td>
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<td>30</td>
<td>2010</td>
<td>Pilot CFB</td>
<td>Anthra.(Pet ck)</td>
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<td>Jamestown</td>
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<td>2013</td>
<td>50 MWe CFB</td>
<td>Bit.</td>
<td>With CCS</td>
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<td>~1000</td>
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<td>~100 MWe PC?</td>
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Oxy-Fuel Combustion Boiler Projects

- Conversion @ 1 MWe = 3 MWt = 10 MMBtu/hr

- Utility
  - Boilers

- Industrial
  - Furnaces

- Utility
  - Furnaces

- ANL/EERC 1.0
- ANL/BHP 0.2
- Test Furnaces 0.2
- CANMET 0.1
- IHI 0.5
- B&W 0.4
- AL 0.1

- International Comb 11.7
- IFRF 1.0
- JSIM/NEDO(oil) 4.0
- Jupiter 6.7
- IVD-Stuttgart 0.3
- ENEL 1.0
- PowerGen 0.3

- Vattenfall 250.0
- Youngdong 100.0
- Callide A 30.0
- Jamestown 50.0
- Pearl Plant 6.7
- CIUDEN 6.7
- TOTAL(NG) 13.3
- Oxy-coal UK 0.0000
- CIUDEN 0.0000
- Jupiter 0.0000
- IVD-Stuttgart 0.0000
- ENEL 0.0000
- PowerGen 0.0000
- RWE-NPOWER 0.0000

- ANL/EERC
- ANL/BHP
- IHI
- B&W
- AL
- CANMET
- IFRF
- JSIM/NEDO(oil)
- Jupiter
- IVD-Stuttgart
- ENEL
- PowerGen
- RWE-NPOWER

Year
Pre-Combustion Capture
(Considering only Coal Power Plant)
Pre-Combustion Capture

IGCC with CO$_2$ capture

Coal → Gasification → Shift conversion → Acid gas removal → CO$_2$ compression → CO$_2$

CO + H$_2$O → H$_2$ + CO$_2$

Air separation → Oxygen → Nitrogen

Fuel gas (mainly H$_2$) → Combined cycle → Power

Oxygen Air

Air

Sulphur recovery → H$_2$S

Sulphur recovery

http://www.ieagreen.org.uk
IGCC without Capture

- 5 coal-based IGCC demonstration plant in the USA, Europe and Japan
- IGCC is not at present the preferred technology for new coal-fired power plants
- Main commercial interest in IGCC is for use of petroleum residues
- Several plants built and planned at refineries
- IGCC has some intrinsic economic advantage over PC plant when CCS is added
IGCC – Currently in Operation

Puertollano, 300 MW el
Premilo, since 1998

Nuon – Buggenum
250 MW el

Tampa, 250 MW el
Mexaco, since 1996

Wabash River, 262 MW el
Dow, since 1995
250MWe Air Blown IGCC (Fukushima, Japan)
CO2 Capture in IGCC

• Advantages of IGCC for CO$_2$ capture
  o High CO$_2$ concentration and high overall pressure
    ▪ Lower energy consumption for CO$_2$ separation
    ▪ Compact equipment
  o Proven CO$_2$ separation technology can be used
  o Possibility of co-production of hydrogen

• Disadvantages
  o IGCC is unfamiliar technology for power generators
  o Existing coal fired plants have low availability
  o IGCC without CO$_2$ capture has generally higher costs than pulverised coal combustion
IGCC

- IGCC with pre-combustion capture has been the fundamental building blocks in various programme for co-generation of electricity and hydrogen
- Some examples
  - USA: FutureGen (old) Programme
  - Europe: HYPOGEN Programme
  - Japan: EAGLE Project
  - China: GreenGen Project
Pre-Combustion Capture: Key Barrier

- Will reliability hinder the deployment of IGCC?

- Record for IGCC’s availability has been poor but improving.

- Complexity of the plant could be a turn off to prospective investors or power generation company

- Cost is another issue

Source: EPRI

http://www.ieagreen.org.uk
Pre-Combustion Capture: Key Development Area

• Development in Gasifier Technology

• Development in Shift Reactor
  ○ Choice of Sour vs Sweet Shift Reaction

• Development in Separation of CO$_2$ using Physical Absorption technology

• Development in the Gas Turbine technology
  ○ Development of gas turbine firing H2 rich fuel using the current DLN technology
What are the current trend of development in IGCC Based Technology...

- New fleet taking advantage of 10+ years of operation in the U.S. and Europe
  - Materials of construction
  - Spare equipment
  - Gasifier refractory / membrane wall
  - Burner design
- Range of suppliers to choose from, for a wide variety of coals and other feedstocks
- EPC alliances can provide important guarantees
GE Bechtel Reference Plant
Concluding Remarks

http://www.ieagreen.org.uk
Power Generation Efficiency

Efficiency, % LHV

- Post-comb
- IGCC slurry
- IGCC dry
- Oxyfuel
- Post-comb
- Oxyfuel

**Coal**

- Without capture
- With capture

**Natural gas**

- Without capture
- With capture

Source: IEA GHG studies

http://www.ieagreen.org.uk
Capital Cost

US $/kW

- Post Fluor
- Post MHI
- IGCC slurry
- IGCC dry
- Oxyfuel

Coal

Natural gas

• Source: IEA GHG studies

• Based on 1 US $/Euro

http://www.ieagreen.org.uk
Cost of Capture and Storage

- Electricity cost, US c/kWh

- Fuel cost, $/GJ (LHV)

Basis: 10% DCF, 25 year life, 85% load factor, $8/t CO₂ stored

http://www.ieagreen.org.uk
Summary

• CCS is one of the important measures that will make a significant impact on reducing CO$_2$ emissions

• CCS implementation is picking up pace internationally
  o Several activities have been initiated worldwide in the development of CO$_2$ Capture for Power Generation industry.

• There are two set of horse race among the three leading CO$_2$ capture options for newly build and retrofit power plant.
  o **There is no clear winner at the moment!**

• We need large scale demonstration of the carbon capture technology to build the confidence necessary for a rapid deployment.

• We also need to build our technical capacity base and encourage students to see CCS as their future career path

http://www.ieagreen.org.uk
Thank You
Any Questions?

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CCS – http://www.co2captureandstorage.info
GHGT-9 – http://www.mit.edu/ghgt9

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