Abstract
Process Economics Program Report 277
COAL TO SUBSTITUTE NATURAL GAS
(November 2010)

What initially prompted the production of substitute natural gas (SNG) in the United States was the concern over volatile natural gas prices, declining gas production and domestic energy security. These factors sparked a revival of interest in developing reliable domestic sources that are decoupled from the world oil market. SNG presents an opportunity for production from cheap and plentiful U.S. coal supplies, and has costs driven by coal prices and plant construction, rather than international energy markets.

The United States has many projects on the horizon for coal-to-SNG, but some of these projects are being delayed due to financing challenges or are being redesigned into another product from coal (instead of SNG) as a result of the recent fall in U.S. gas prices.

On the other hand, China’s coal-to-SNG projects are progressing at full speed because China’s gas prices are approximately 2–3 times higher than those in the United States. China has traditionally imported most of its gas either via pipeline from Russia or it has been shipped in as liquefied natural gas (LNG). Making its own SNG is one way for China to use its large coal assets rather than importing energy. China already has excellent logistics for moving coal with the existing rails and roadways. Therefore the delivery of SNG energy to the marketplace may occur through the existing and expanding pipeline infrastructure.

The main focus of this report is evaluating the techno-economics of SNG production from coal by the Shell gasification process integrated with the Haldor Topsoe TREMP™ methanation technology. The base case cost estimates are for producing 78 billion scf/yr of substitute natural gas that is of pipeline quality.
COAL TO SUBSTITUTE NATURAL GAS

by Dipti Dave
with contributions by
Ron Smith

November 2010

Menlo Park, California 94025
SRIC agrees to assign professionally qualified personnel to the preparation of the
Process Economics Program's reports and will perform the work in conformance with generally
accepted professional standards. No other warranties expressed or implied are made. Because
the reports are of an advisory nature, neither SRIC nor its employees will assume any liability for
the special or consequential damages arising from the Client's use of the results contained in the
reports. The Client agrees to indemnify, defend, and hold SRIC, its officers, and employees
harmless from any liability to any third party resulting directly or indirectly from the Client's use of
the reports or other deliverables produced by SRIC pursuant to this agreement.

For detailed marketing data and information, the reader is referred to one of the SRI
Consulting programs specializing in marketing research. THE CHEMICAL ECONOMICS
HANDBOOK Program covers most major chemicals and chemical products produced in the
United States and the WORLD PETROCHEMICALS PROGRAM covers major hydrocarbons and
their derivatives on a worldwide basis. In addition the SRIC DIRECTORY OF CHEMICAL
PRODUCERS services provide detailed lists of chemical producers by company, product, and
plant for the United States, Western Europe, Canada, and East Asia, South America and Mexico.
| CONTENTS |
|-------------------------------|-----------------|
| GLOSSARY | xii |
| 1  INTRODUCTION | 1-1 |
| 1.1  BACKGROUND | 1-1 |
| 1.2  COAL TO SNG DRIVERS FOR COMMERCIALIZATION | 1-3 |
| 1.3  SNG PRODUCT SPECIFICATIONS | 1-3 |
| 1.4  REPORT OVERVIEW | 1-4 |
| 2  SUMMARY | 2-1 |
| 2.1  EXISTING COMMERCIAL PRODUCTION | 2-1 |
| 2.1.1  History and Markets | 2-2 |
| 2.1.2  Technology Overview | 2-2 |
| 2.1.3  Steam Oxygen Gasification | 2-3 |
| 2.1.4  Hydrogasification | 2-3 |
| 2.1.5  Catalytic Steam Gasification | 2-3 |
| 2.1.6  METHANATION | 2-4 |
| 2.1.7  Catalytic Methanation | 2-5 |
| 2.1.8  Direct Methanation | 2-5 |
| 2.1.9  HICOM Methanation | 2-6 |
| 2.1.10  Liquid Phase Methanation | 2-6 |
| 2.1.11  Haldor Topsoe TREMP™ Methanation Technology | 2-6 |
| 2.1.12  Economics | 2-8 |
| 2.1.13  Conclusions | 2-9 |
| 3  INDUSTRY STATUS | 3-1 |
| 3.1  BACKGROUND | 3-1 |
| 3.2  INTRODUCTION | 3-2 |
| 3.3  A Brief Historical Perspective | 3-3 |
| 3.4  DOE’s Survey of Substitute Natural Gas | 3-5 |
CONTENTS (Continued)

COAL OVERVIEW .....................................................................................................3-7
Coal Gasification Industry ...........................................................................................3-11
Drivers for Coal Gasification .......................................................................................3-18
  Oil and Gas Prices ..................................................................................................3-18
  Energy Security ......................................................................................................3-20
  Environmental Policy .............................................................................................3-20

DOMESTIC PROJECT OUTLOOK ...............................................................................3-21
United States ..............................................................................................................3-21

INTERNATIONAL PROJECT OUTLOOK ..................................................................3-24
Japan ..........................................................................................................................3-24
China ..........................................................................................................................3-24
South Korea ...............................................................................................................3-26

COAL TO SNG DRIVERS ..........................................................................................3-27

SNG PRODUCT QUALITY .........................................................................................3-27

COAL AS A RESOURCE ...........................................................................................3-28
Chinese Coal Industry ...............................................................................................3-29

4 TECHNICAL REVIEW ..............................................................................................4-1

INTRODUCTION ........................................................................................................4-1
Gasification Sasol-Lurgi ..............................................................................................4-1

CURRENT COMMERCIAL PRODUCTION ...............................................................4-2
Great Plains Synfuels Plant .......................................................................................4-3
Great Plains Synfuels Original Plant .........................................................................4-4

Coal Handling .............................................................................................................4-5
Air Separation Unit ......................................................................................................4-6
Great Plains Lurgi Dry Bottom Gasifier .....................................................................4-6
Alternative Gasifiers and Feedstocks .........................................................................4-8
Ash Handling ...............................................................................................................4-8
CONTENTS (Continued)

Shift Conversion and Gas Cooling ................................................................. 4-9
Rectisol .............................................................................................................. 4-9
Great Plains North Dakota Methanation ......................................................... 4-10
METHANATION ................................................................................................. 4-11
Catalyst Fouling ............................................................................................... 4-12
Catalysts ........................................................................................................... 4-13
Direct Methanation .......................................................................................... 4-14
HICOM Methanation ......................................................................................... 4-14
Liquid Phase Methanation .............................................................................. 4-15
Haldor Topsoe TREMP™ Methanation Technology ......................................... 4-15
Methanation by Split Cold Gas Recycle .......................................................... 4-17
Split Stream Methanation .............................................................................. 4-18
Methanation by Reactors in Series ................................................................. 4-21
Methanation Process by Shell ....................................................................... 4-22
ALTERNATIVE GASIFICATION TECHNOLOGIES ........................................ 4-24
Steam Oxygen Gasification ............................................................................ 4-24
Hydrogasification ............................................................................................ 4-24
Advanced Hydrogasification .......................................................................... 4-25
Hydrogenator by British Gas ......................................................................... 4-27
Catalytic Steam Gasification .......................................................................... 4-30
Shell Catalytic Gasification ............................................................................ 4-30
CONVENTIONAL GASIFICATION VARIANT TECHNOLOGY ......................... 4-31
Gasification for SNG and Power Production ................................................. 4-32
Two Stage Gasification for SNG Power Production ....................................... 4-34
Two Stage Gasification Plus Two Step Methanation .................................... 4-35
Non-Fossil-Derived Hydrogen Utilization for Coal Conversion ...................... 4-37
Coal Minerals Catalytic Activity Impact on Hydrogasification ....................... 4-38
CONTENTS (Continued)

Hydrogasification Apparatus and Method for Producing Methane......................... 4-38
Hydrogasification for SNG and Power........................................................................ 4-41
Hydrogasification Reactor .......................................................................................... 4-42
Catalytic Steam Gasification....................................................................................... 4-43

5 SUBSTITUTE NATURAL GAS FROM COAL BY HALDOR TOPSOE TREMP™ METHANATION PROCESS ................................................................. 5-1

MAIN REACTIONS ..................................................................................................... 5-1
Catalysts ..................................................................................................................... 5-3
Sulfur Removal ........................................................................................................... 5-4

REVIEW OF COAL GASIFICATION PROCESS ....................................................... 5-4
Gasification Pressure ................................................................................................. 5-5
Gasifier Fuel ............................................................................................................... 5-5
Heat Recovery Systems ............................................................................................. 5-6
Features of the Shell Gasifier ..................................................................................... 5-7

PROCESS DESCRIPTION ........................................................................................ 5-7
Fuel Feed System ...................................................................................................... 5-7
Extent of CO₂ Removal............................................................................................... 5-8
  Carbonyl Hydrolysis............................................................................................... 5-8
  Mercury Removal ................................................................................................... 5-8
  Acid Gas Removal ................................................................................................. 5-9
  Shift Converter....................................................................................................... 5-10
  Sulfur Recovery and Tailgas Treating................................................................... 5-10

BASIS FOR DESIGN AND EVALUATION ................................................................. 5-10

PROCESS DESCRIPTION ........................................................................................ 5-14
Section 100—Coal Receiving and Storage ............................................................... 5-15
Section 200—Air Separation Plant ........................................................................... 5-15
Section 300—Coal Preparation and Gasification ...................................................... 5-16
Section 400—Shift, Cooling and Mercury Removal ................................................ 5-17
CONTENTS (Concluded)

Section 500—CO₂ Removal and Rectisol ................................................................. 5-18
Section 600—Claus/SCOT .................................................................................... 5-18
  Claus Sub-Section ............................................................................................. 5-18
  SCOT Sub-Section ............................................................................................ 5-19
Section 700—Haldor Topsoe TREMP™ Methanation Process ......................... 5-20
Section 800—SNG Drying ................................................................................... 5-21
  Stream Flows .................................................................................................... 5-21
STEAM GENERATION ........................................................................................... 5-26
  Steam Balance .................................................................................................. 5-26
    High Pressure Steam ..................................................................................... 5-26
    Medium Pressure Steam ............................................................................... 5-26
    Low Pressure Steam ..................................................................................... 5-26
      Steam Pressure 150 psig .......................................................................... 5-26
      Steam Pressure 50 psig ........................................................................... 5-26
COST ESTIMATES ................................................................................................. 5-27
  Fixed-Capital Costs ......................................................................................... 5-28
  Production Costs .............................................................................................. 5-28
CONCLUSION ....................................................................................................... 5-28

APPENDIX A  PATENT SUMMARY TABLES ......................................................... A-1

APPENDIX B  DESIGN AND COST BASES ....................................................... B-1

APPENDIX C  CITED REFERENCES .................................................................... C-1

APPENDIX D  PATENT REFERENCES BY COMPANY ....................................... D-1

APPENDIX E  PROCESS FLOW DIAGRAMS ...................................................... E-1
FIGURES

3.1 Energy Demand by Region—2008, mTon ............................................................ 3-2
3.2 U.S. Natural Gas Consumption by Region ............................................................ 3-6
3.3 U.S. Natural Gas Consumption by Sector ............................................................ 3-7
3.4 Coal Reserves by World Region (2009) ............................................................. 3-8
3.5 Coal Demand by World Region (2009) ............................................................... 3-9
3.6 U.S. Coal Demand (2009) .................................................................................... 3-10
3.7 Fuel Cost at Electricity Generating Plants ............................................................. 3-10
3.8 World Gasification Capacity by Fuel Type (MNm³/Day) ........................................ 3-12
3.9 Cumulative Growth in World Gasification Capacity (MNm³/Day).......................... 3-13
3.10 Coal Gasification Capacity by Region (MNm³/Day) ............................................. 3-14
3.11 Coal Gasification Capacity by Product ............................................................... 3-15
3.12 Coal Gasification Capacity by Technology (MNm³/Day) ..................................... 3-16
3.13 Coal Gasification to Chemicals ........................................................................... 3-16
3.14 Coal Gasification to Power ................................................................................. 3-17
3.15 Gasification Plants and Technology .................................................................... 3-17
3.16 Historical Fuel Prices ......................................................................................... 3-19
3.17 Historical Coal and Natural Gas Price ............................................................... 3-20
3.18 Energy Consumption by Sector ........................................................................ 3-30
4.1 Temperature Profile for Moving or Fixed-Bed Gasifier ..................................... 4-2
4.2 Simplified Process Diagram for SNG Production .............................................. 4-4
4.3 Flow Scheme for Some of the Major Process Steps of the Original SNG Plant Design ........................................................................................................ 4-5
4.4 Lurgi Dry Bottom Gasifier .................................................................................. 4-7
4.5 Graph for Absorption Coefficients ...................................................................... 4-9
4.6 Basic Catalytic Methanation Scheme .................................................................. 4-10
4.7 Relationship between H₂/CO Ratio, Temperature and Carbon Deposition ........ 4-13
4.8 Haldor Topsoe TREMP™ Process Scheme ...................................................... 4-16
4.9 Fixed-Bed Catalytic Methanation Scheme ........................................................... 4-17
FIGURES (Concluded)

4.10 Split Stream Methanation Block Flow Diagram ............................................. 4-20
4.11 Methanation Scheme with Reactors in Series ............................................. 4-22
4.12 Process Flow Schematic Shell Methanation .................................................. 4-23
4.13 Steam-Oxygen Gasification Process Block Flow Diagram .......................... 4-24
4.14 Hydrogasification Process Block Flow Diagram ........................................... 4-25
4.15 Integrated Advanced Hydrogasification ....................................................... 4-26
4.16 Entrained Flow Reactor ............................................................................... 4-28
4.17 Coal Hydrogenation Process Scheme ......................................................... 4-29
4.18 Catalytic Steam Gasification Process Block Flow Diagram ........................ 4-30
4.19 Gasification for SNG Power Production ...................................................... 4-33
4.20 Two Stage Gasification for SNG Power Production .................................... 4-34
4.21 Two Stage Gasification by Two Step Methanation for SNG Production ....... 4-36
4.22 Hydrogasification Process Scheme ............................................................... 4-39
4.23 Hydrogasification Block Flow Diagram ....................................................... 4-41
4.24 Hydrogasification Reactor ........................................................................... 4-42
5.1 Coal to SNG Process Process Flow Diagram ............................................... E-3
5.2 Haldor Topsoe TREMP™ Technology Process for Methanation Process Flow Diagram .................................................. E-5
5.3 Coal to SNG Steam Balance Process Flow Diagram ..................................... E-7
# TABLES

1.1 Recoverable Energy Reserves and Distribution of Energy Resources ............ 1-2
1.2 Pipeline Quality Natural Gas Ranges................................................................. 1-4
2.1 Comparison of Coal to SNG Processes.............................................................. 2-4
2.2 Coal to SNG Coal Gasification Operating Configuration and Operating Conditions........................................................................................................... 2-8
2.3 Process Economics SNG Production from Coal by Haldor Topsoe TREMP™ Methanation Technology ................................................................. 2-9
3.1 Coal to SNG Projects in the United States....................................................... 3-22
3.2 Proposed SNG Projects in the United States.................................................... 3-24
3.3 Coal to SNG Projects in China......................................................................... 3-25
3.4 Pipeline Quality Natural Gas Ranges................................................................. 3-28
4.1 Alternative Gasifier Types and Coal Feedstocks.............................................. 4-8
4.2 Enhancement of Reactivity of Coal by Use of an Additive.............................. 4-31
4.3 Comparison of Coal to SNG Processes............................................................ 4-44
5.1 Gasification Chemistry..................................................................................... 5-2
5.2 Haldor Topsoe TREMP™ Methanation Reactions........................................... 5-2
5.3 DOE Illinois #6 Coal Composition (Wet, Ash Free)........................................ 5-6
5.4 Features of Shell Dry Feed Gasifier.................................................................. 5-7
5.5 Design Specifications for Gas Clean up Systems.............................................. 5-8
5.6 Process Sections............................................................................................... 5-11
5.7 Basis for Estimates and Evaluations—SNG from Coal by Haldor Topsoe TREMP™ Methanation Process .......................................................... 5-12
5.8 Raw Syngas Composition Specification............................................................ 5-15
5.9 SNG from Coal by Haldor-Topsoe TREMP™ Methanation Process Stream Flows........................................................................................................... 5-22
5.10 Low Pressure Steam Balance......................................................................... 5-27
5.11 Coal to SNG
    Total Capital Investment.................................................................................. 5-30
5.12 Coal to SNG
    Production Costs............................................................................................. 5-31

© SRI Consulting

X

PEP Report 277
TABLES (Concluded)

5.13 Coal to SNG
Utilities Summary................................................................................................... 5-33

5.14 Methanation and SNG Drying
Utilities Summary................................................................................................... 5-35

5.15 Methanation and SNG Drying
Total Capital Investment........................................................................................ 5-36

5.16 Methanation and SNG Drying
Production Costs ................................................................................................... 5-37

5.17 Methanation and SNG Drying
Major Equipment ................................................................................................... 5-39