Road to Hydrogen Society:
Innovation and Japan-US collaboration
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Development of Carbon-free Hydrogen Value Chain

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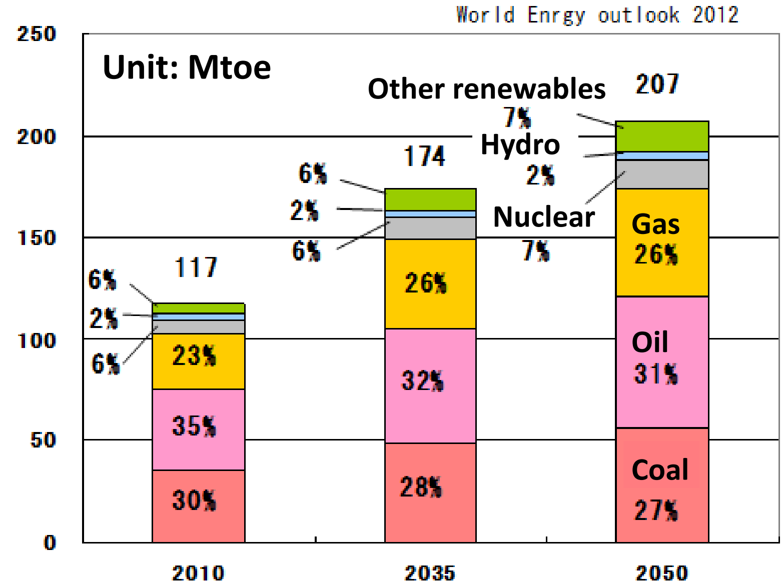
Increase of world energy demand and CO_2 constraint

Increase of world energy demand

- **Demand of the world primary energy will:**
  Increase 180% by 2050 (base year: 2010).
- **Demand on the world fossil fuels will:**
  Increase 170% by 2050 (base year: 2010).
- **Most of demand increase will occur in Asian region.**

(IEA World Energy Outlook 2012)



「Paris Treaty」 of the UNFCCC

- "2℃ goal" was set as the long-term temperature goal. Moreover, "1.5℃ goal" was mentioned as the goal to be pursued.
- Upper end of 40～70% level of the CO_2 emission reduction may be required by 2050.

Japan's proposal on the long term CO_2 emission reduction goal

- **50% emission reduction in the world by 2050.**
- **80% emission reduction by industrialized countries by 2050.**

Towards hydrogen society

Diversification of energy sources

Stabler energy supply

De-carbonization

→ **Use of hydrogen energy**

SIP (Cross-Ministerial Strategic Innovation Promotion Program)

Five-year program for innovation by comprehensive policy measures, such as promotion of basic, applied and development research, deregulations and other institutional reforms.

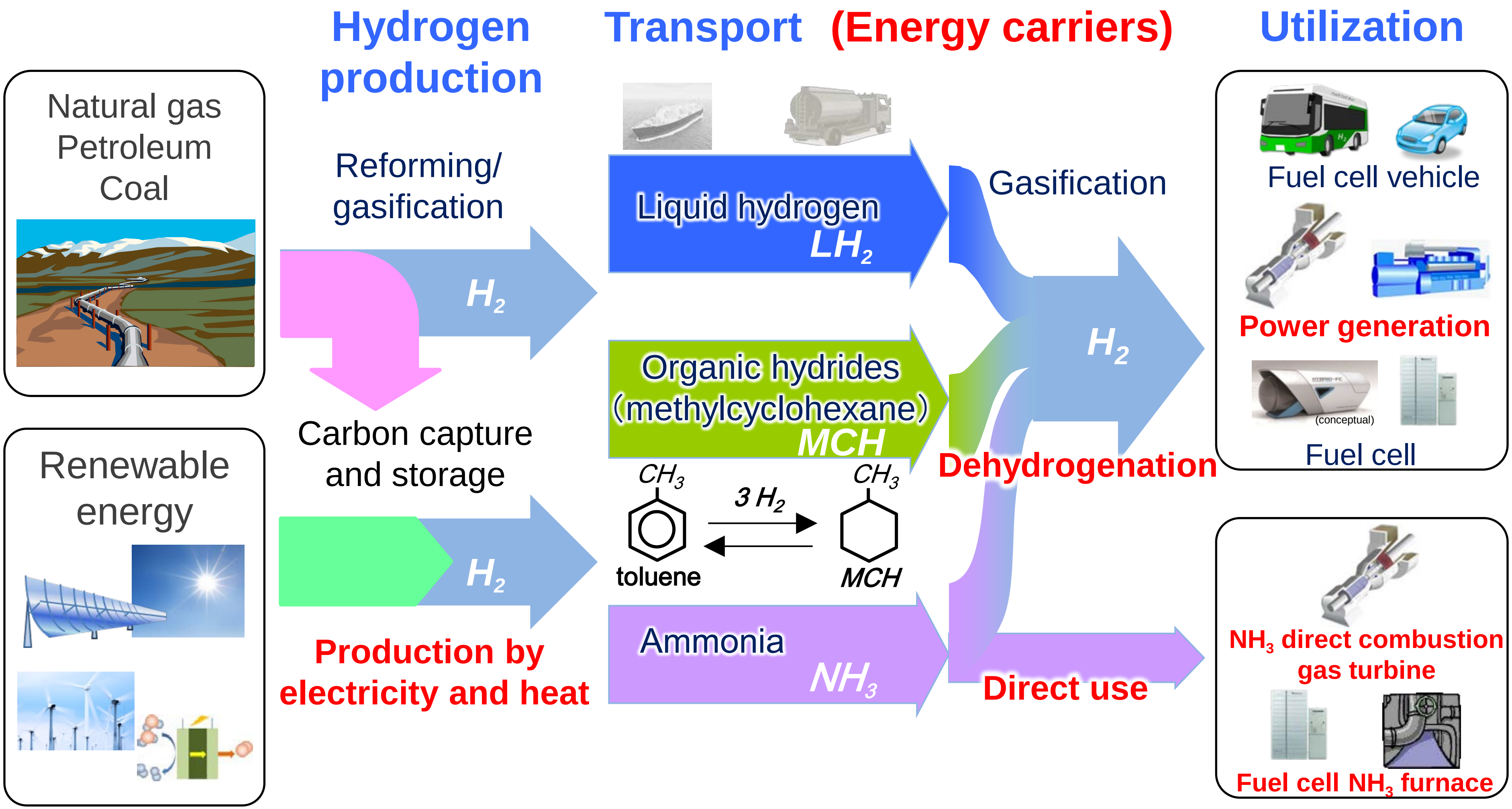
- ☐ Involving various ministries and academic/business sectors
- ☐ Resources centrally allocated by Council for STI (CSTI)
- ☐ Program Director appointed by Prime Minister

SIP (Cross ministerial strategic innovation promotion program)

	Themes	Agency	2015 Budget (BJPY)
Energy	Innovative Combustion Technology	**JST**	2.0
	Next-generation Power Electronics	NEDO	2.4
	Structural Materials for Innovation	**JST**	3.9
	Energy Carriers	**JST**	**3.3**
	Next-generation Technology for Ocean Resources Exploration	JAMSTEC	5.7
Next-generation Infrastructures	Automated Driving System	CAO/MIC/ METI/MLIT	2.4
	Infrastructure Maintenance, Renovation and Management	**JST**/NEDO	3.4
	Enhancement of Societal Resiliency against Natural Disasters	**JST**	2.6
Utilization of Regional Resources	Technologies for Creating Next-generation Agriculture, Forestry and Fisheries	NARO	3.4
	Innovative Design/Manufacturing Technologies	NEDO	2.6
	Cyber Security of Critical Infrastructures	NEDO	0.5

Strategy of SIP Energy Carriers

~ Development of CO_2 free hydrogen value chain ~



Strategy for Energy Carriers development

Vision	Japan as a role model for world's first low carbon society utilizing hydrogen by 2030

2015-2020	2020-2030	2030 —
Commercialization of fuel cell vehicle, residential fuel cell cogeneration	Expansion of fuel cell markets Introduction of hydrogen power generation	Commercialization of large-scale hydrogen power plant Large-scale deployment of carbon free hydrogen
Development of technologies for carbon free hydrogen production, energy carrier and their utilizations Demonstration of hydrogen society at 2020 Tokyo Olympics and Paralympics	Demonstration of high efficient power generation using hydrogen and energy carrier from small scale up to large scale	High presence of Japanese hydrogen relevant industries in the global market

Research & Development subjects in SIP

Hydrogen-related research subjects

High-temperature solar thermal energy supply system

Production of hydrogen using heat

Unloading system for liquefied hydrogen (at ports)

C. Liquefied hydrogen combustion gas turbine and engine

Ammonia-related research subjects

Production

↓

Carrier transformation
Transportation
Storage

↓

Utilization

Ammonia production using distributed energy system

De-hydrogenation system for hydrogen station using ammonia as an energy carrier

A. Ammonia fuel cells

B. Direct combustion of ammonia for gas turbine and industrial furnace

Organic hydrides-related research subjects

Electrolytic synthesis of organic hydrides

On-site hydrogen production from methyl-cyclohexane at hydrogen station

Health and environmental risk analysis of energy carriers

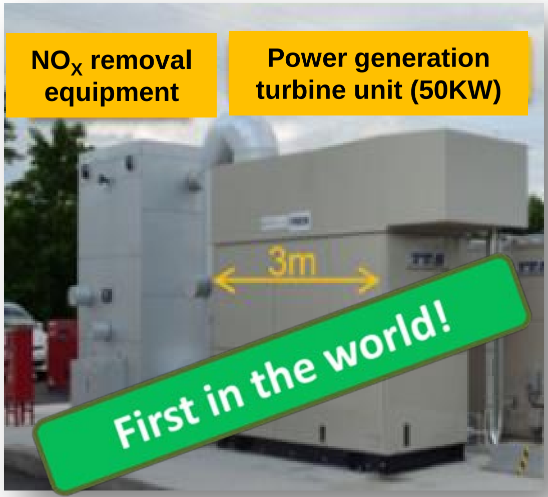
Major Research Achievements in 2015

A. Ammonia direct supply fuel cell（SOFC)

- Developed an ammonia-fueled cell stack (direct supply of ammonia as fuel) and successfully generated 200 W
- Performance equivalent to the hydrogen supply type fuel cell

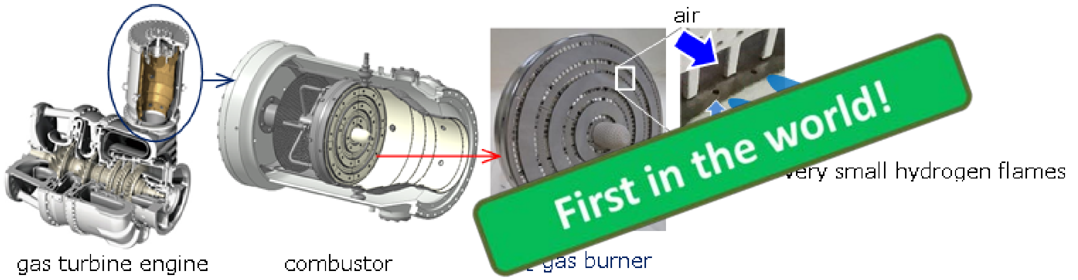
B. Ammonia combustion turbine

- Successful power generation with multi-fuel (CH_4 and NH_3) and single-fuel (NH_3 only) turbines
- Optimized operating conditions for NO_X removal equipment



C. Hydrogen gas turbine

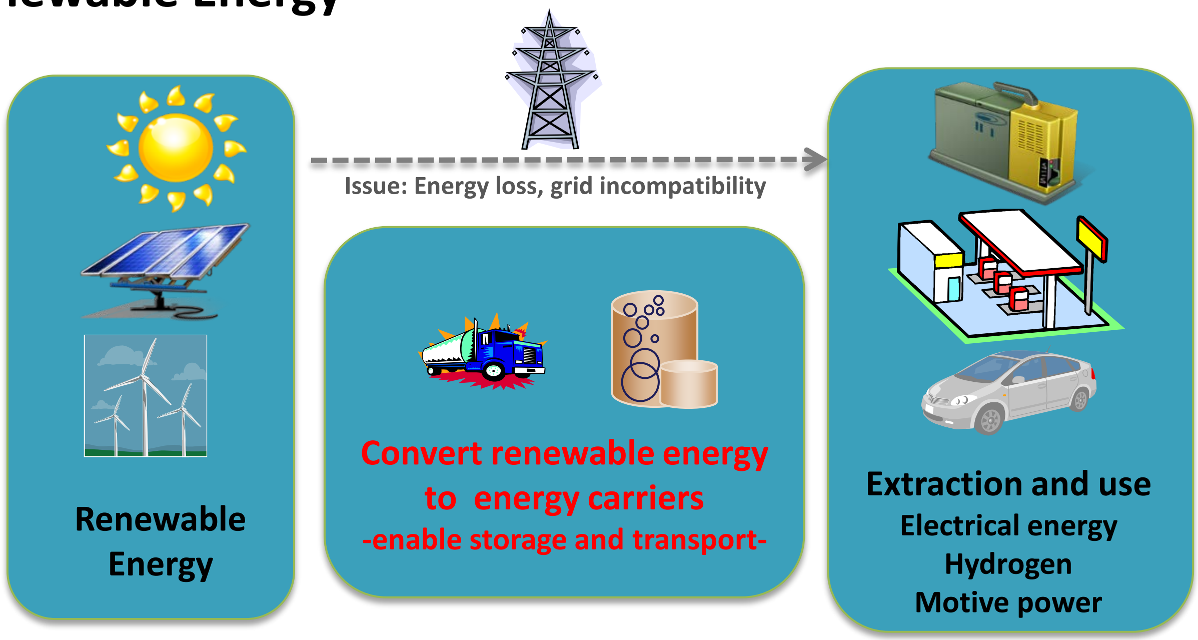
- Developed dry-Low-Emission combustion technology
- Prevention of unstable H_2 combustion and reduced emission of NO_X (<40ppm) in gas turbines on 100% hydrogen fuel



Research Programs: CREST, PRESTO

"Creation of Innovative Core Technology for Manufacture and Use of Energy Carriers from Renewable Energy"

Research Supervisor
Professor Koichi Eguchi
Kyoto University, Japan



This research area, looking ahead to a hydrogen energy society making stable and efficient use of renewable energy, ***aims to create fundamental and core technology for (1) efficient conversion of renewable energy to energy carriers that store and transport chemical energy,* and *(2) for extraction and use of electrical energy, hydrogen, and motive power, etc., from the energy carriers.***
JST conducts 21 basic research projects (5 years- and 3 years-projects) since 2013, under the supervision of Prof. Koichi Eguchi.
Energy carriers targeted here are ammonia, organic hydrides, formic acid, and others.
*CREST and PRESTO programs are

Appendix

Overview of R&D projects relating to hydrogen energy

Themes conducted under SIP "Energy Carrier"

H_2 source → H_2 production → Energy Carrier production, large volume transportation and storage system → Use

H_2 source

Fossil fuels

Steel works
Refineries
Petro Chemical Plants

Oil fields
Gas fields
Coal mines
Lignite , etc.

Water + Renewable energy

Hydro power
Wind Farms
CSP
Photo voltaic, etc.

H_2 production

Reforming

- By-product H_2
- Gasification
- Steam reforming

Water Electrolysis

- Solid Polymer Water Electrolysis
- Water Electrolysis Using Neutral Water
- Alkaline water electrolysis
- SOEC
- Next generation electrolysis

(1)Production of H_2 using CSP technology
- CSP

Energy Carrier production, large volume transportation and storage system

On-site reforming

H_2(Gas)
- Transportation of H_2 gas in high pressured vessel

Methane
- High Efficiency Methanation System

Liquefied H_2 (LH_2)
- Storage system (Tank, LH_2 pump)
- (4)Utilization tech. of LH_2
  - Unloading system for LH_2 (at port)

Organic hydride
- Dehydrogenation using Silica membrane
- (3) Energy Carrier: Organic Hydride
  - Dehydrogenating tech. using Carbon membrane
  - Electrolytic synthesis
  - → H_2 Station

Ammonia
- Molten Salt Electrolysis Synthesis
- Innovative NH_3 Synthesis
- (2) Energy Carrier : NH_3
  - NH_3 production using dispersed energy
  - Dehydrogenating tech. → H_2 Station
  - Direct Use → NH_3 direct combustion, NH_3 Fuel Cell

(5) Risk analysis of Energy Carrier

Use

- ENE-FARM
- FCV
- H_2 Station
- Fuel Cell for industry & business use
- FCV Bus, Forklift, Garbage Truck
- Renewable energy based H_2 ST
- H_2 Gas Turbine
- H_2 Engine

Ministries & Agencies

- SIP themes
- ANRE of METI
- METI
- MEXT
- EPA

【Safety regulations and standards makings 】 Relevant ministries and agencies

Why Ammonia?

Ammonia seems to be a promising Energy Carrier, because:

(a) Ammonia has high volume hydrogen density;

(b) Ammonia does not emit CO_2 in combustion;

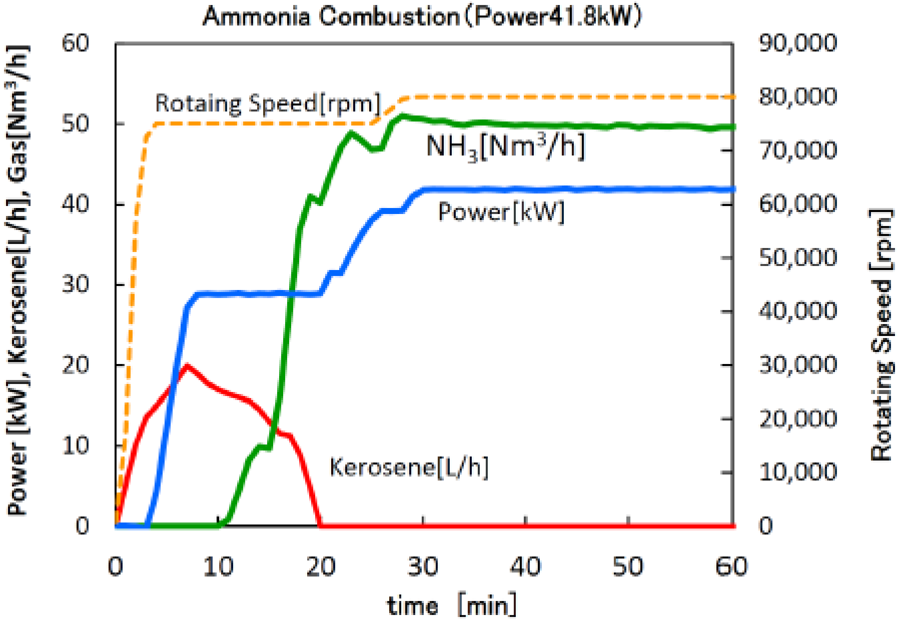
(c) Existing transportation and storage infrastructure can be used;

(d) Ammonia seems to be a promising CO_2 free fuel for gas turbines, fuel cells and industrial furnaces;

NH_3/air flame using a swirl burner

【Source】
Professor Kobayashi
Institute of Fluid Science
Tohoku University

100% Ammonia combustion in Micro Gas Turbine



【Source】Dr. N. Iki, AIST, Japan

Cost comparison of thermally equivalent hydrogen & ammonia

"Strategic roadmap for hydrogen fuel cells"（2014.6）

Assuming 30 JPY.Nm³ in the late 2020's, target was set to achieve cost of Power generation lower than 17 JPY/kWh

Table: Comparison of costs on thermal energy equivalent basis

	Lower Heating Value
Hydrogen	30 JPY/Nm^3
↑	336 JPY/kg
Ammonia	**39.8 JPY/Nm^3**
↑	**51.7 JPY/kg**

⇨ Ammonia (52 JPY/kg, ca 470 ＄/t) is thermally equivalent to hydrogen (30 JPY/Nm^3)

Ammonia: Market Price and Production Cost

Trend of market price of Ammonia

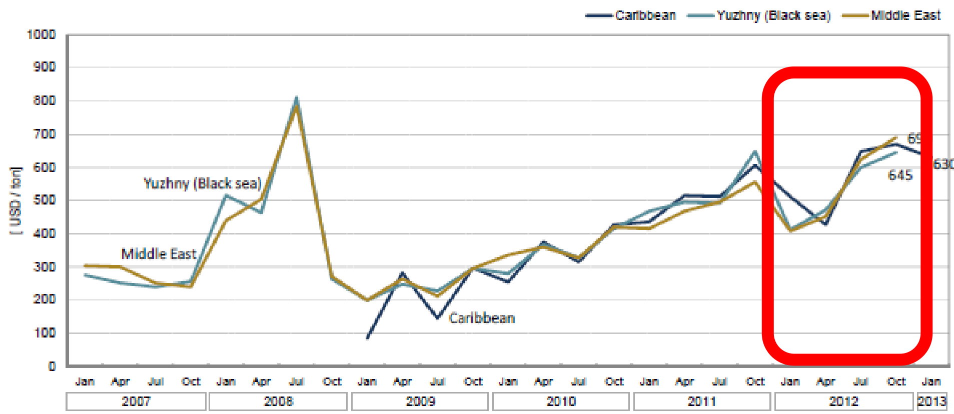


図 2.2-17 アンモニアの価格推移

出所）ICIS pricing, Global fertilizer trade map 及び FERTECON Ammonia Report を基に三菱総合研究所作成

Ammonia Production Cost (Mitsubishi Research Institute, Inc.)

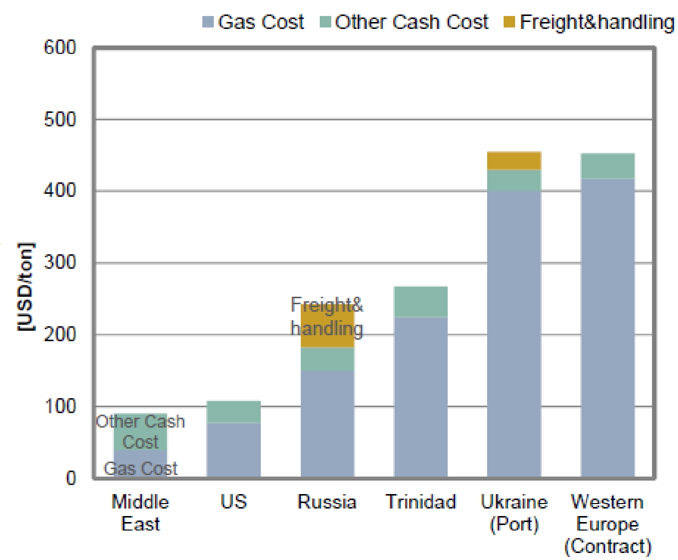


図 2.2-18 アンモニアの製造原価

注）製造原価は 2012 年の天然ガス予測価格を基に算出したもの

出所）Fertecon 資料を基に三菱総合研究所作成

○Trend of market price of Ammonia : 400～700 ＄/ton in 2012

○Production Cost in Middle Est : 100 $ /ton

⇒ Production cost of Ammonia using cheap natural gas is low.
It would be possible as CO_2 free fuel to use it with CCS or EOR.

エネルギーとしての用途が拡大した場合のアンモニア価格の変化の可能性（私見）

◆近年、天然ガスの供給の拡大や需要地域の変化にともなって、世界の市場の構造は変化する兆しを見せている。

◆アンモニアの需要の拡大にともなって、尿素需要動向にかかわらず、アンモニアの供給を目的とする製造プラントが出てくる可能性。

◆アンモニア需要の増大により、アンモニアの供給源として安価な天然ガスを利用して製造した供給源が増加する可能性。

◆これらにより、アンモニア需給構造、価格形成メカニズムが大きく変化する可能性。

◆天然ガスの量的入手可能性、入手可能地域（アンモニア生産＋積み出しの可能性）、入手可能条件などについて調査が必要。

⇨ 現在、調査中。

*Enhanced Oil Recovery：油田にCO2を吹き込んで産出を促す

◆中期的には、CO_2フリーアンモニアの入手が必要。天然ガスからのアンモニア製造でも、CO_2のCCSへの貯留、EOR*向けの活用などにより、一定量のCO_2フリーアンモニアはLNGと競合可能な価格水準で入手可能と見られる。

◆さらには、（再エネ由来等の）CO_2フリー水素を原料とするCO_2フリーアンモニアの確保に向けた取り組みが必要。
⇒　水素を原料とする高効率アンモニア生産プロセスの開発。
⇒　安価な再エネ水素等のCO_2フリーの入手。