IEA ETSAP Workshop 2016, The University of Tokyo, Tokyo

Integrated Assessment of the Prospects for Hydrogen Technology through 2100 using a Regionally Disaggregated DNE21

December 14, 2016

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The University of Tokyo

This work was supported by JSPS KAKENHI Project/Area Number 15H01785.

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1. Introduction

1-1. Background

1-2. Objective of this study

1-1. BACKGROUND

- Hydrogen technology such as fuel cell has been regarded as one of effective measures to reduce carbon emissions.

- Hydrogen energy, however, is just a secondary energy carrier, and its effectiveness should be evaluated considering the whole lifecycle chain of hydrogen production, transportation and consumption.

- Therefore, energy modeling analysis on hydrogen energy is significant.

* Fujii, Y. and Komiyama, R., Chapter 5: Long-Term Energy and Environmental Strategies, J. Ahn et. al. (Eds) Reflections on the Fukushima Daiichi Nuclear Accident: Toward Social-Scientific Literacy and Engineering Resilience, Springer, 2014

WE-NET (WORLD ENERGY NETWORK) PROJECT (1993-2002)

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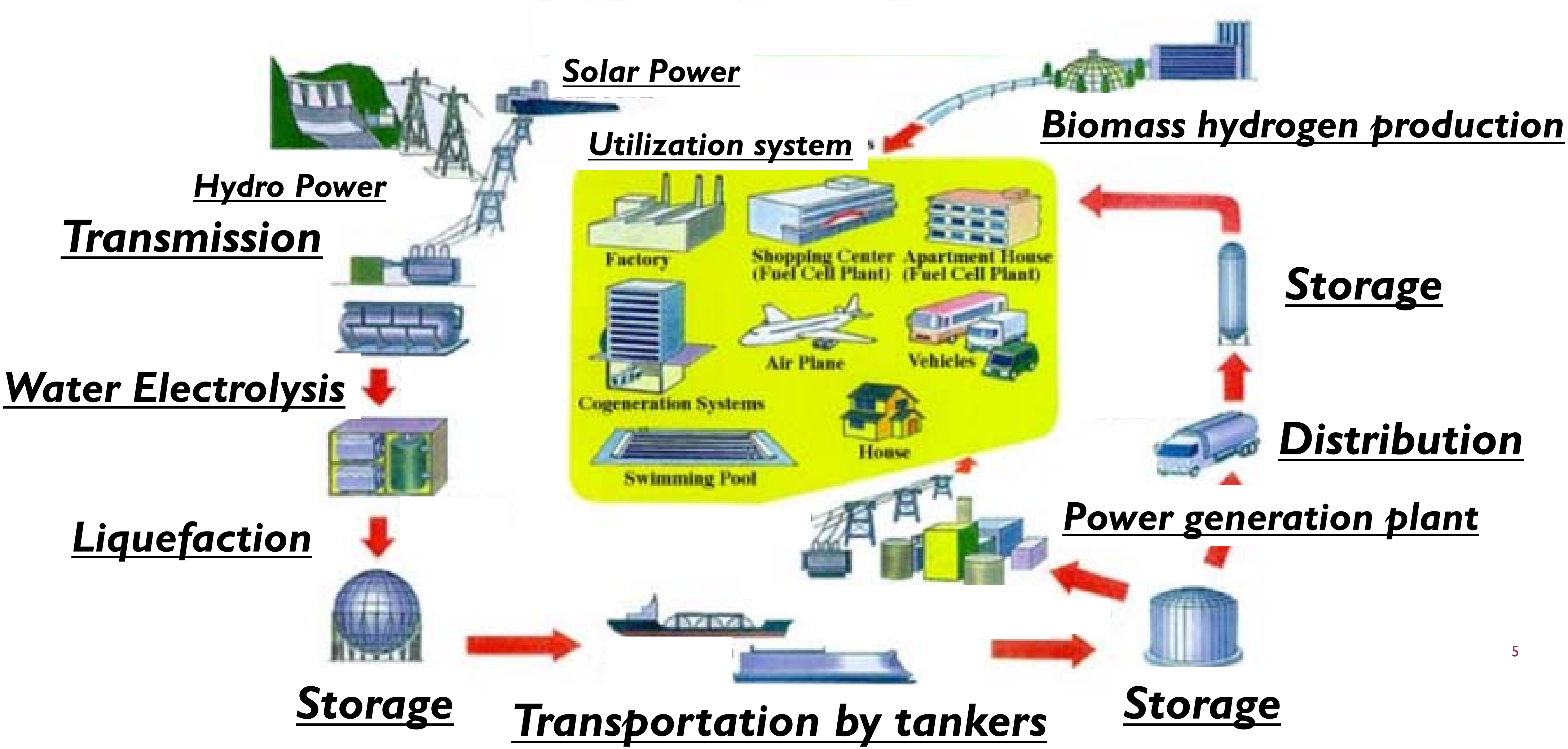


HYDROGEN ENERGY POLICY OF THE WORLD

- U.S.
  Strategetic plan by DOE (H_2USA partnership, H_2FIRST project)
- Europe
  The Fuel Cells and Hydrogen Joint Undertaking （FCH JU)
- UK
  UK H_2 Mobility
- Germany
  NIP（National Innovation Programme Hydrogen and Fuel Cell Technology）
- Japan
  Strategic Energy Plan(April, 2014)

1-2. OBJECTIVE

- Objective is to analyze hydrogen energy with global energy model (DNE21*) considering the whole process of hydrogen energy system.

* Fujii, Y. and Komiyama, R., Chapter 5: Long-Term Energy and Environmental Strategies, J. Ahn et. al. (Eds) Reflections on the Fukushima Daiichi Nuclear Accident: Toward Social-Scientific Literacy and Engineering Resilience, Springer, 2014

2. Methodology

2-1. Global Energy Model(DNE21)

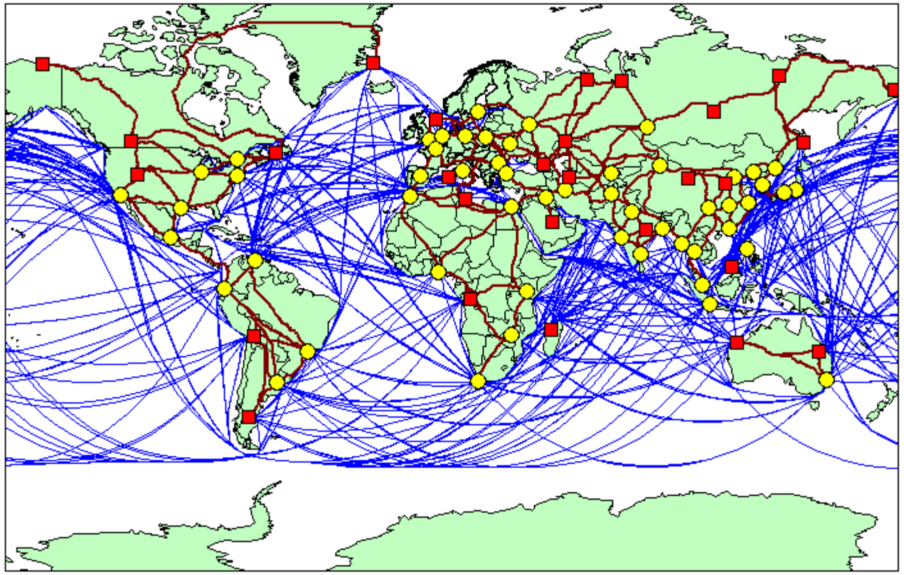
2-2. Key parameters of hydrogen production and transportation

2-3. Scenario and carbon regulation

2-1. Global Energy Model (DNE21)

- Geographical Resolution: 54 regions (82 nodes)
- Detailed consideration for Energy Transport:
  - Pipeline Transport, Tanker Transport, Power Transmission
  - Oil, Gas, Coal, Hydrogen, CO_2, Methanol, Electricity

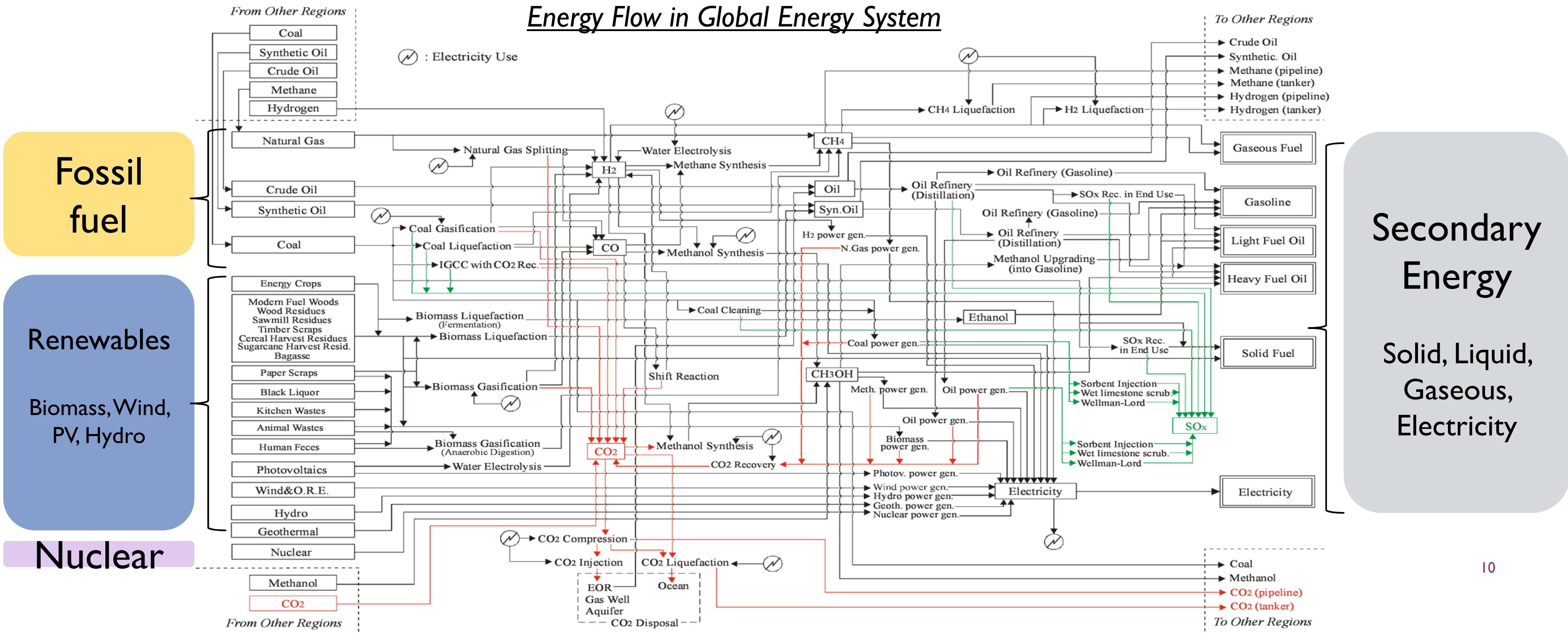
Regional Resolution & Energy Transportation Routes



(Source) Fujii, Y. and Komiyama, R., Chapter 5: Long-Term Energy and Environmental Strategies, J. Ahn et. al. (Eds) Reflections on the Fukushima Daiichi Nuclear Accident: Toward Social-Scientific Literacy and Engineering Resilience, Springer, 2014

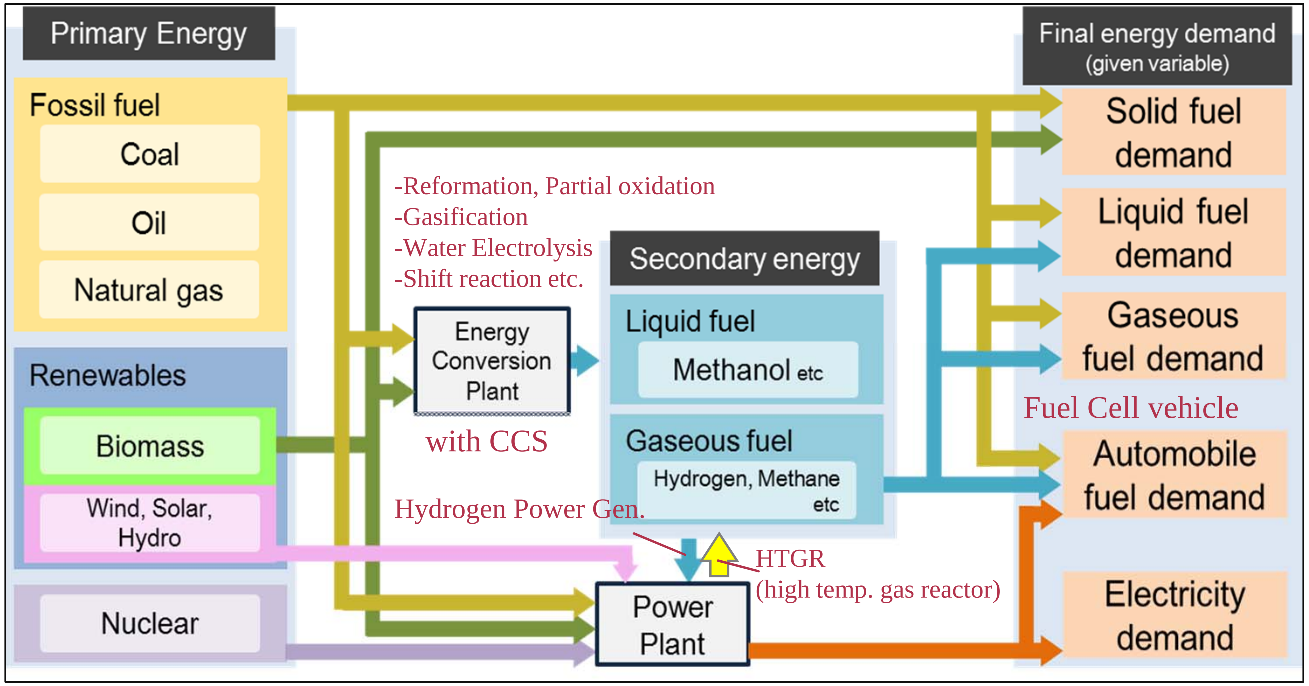
2-1. Global Energy Model (DNE21)

- Cost minimization model (minimization of discounted total cost from 2000 to 2100)
- Scale of model: 24 million constraints, 16 million endogenous variables



2-1. Hydrogen Flow in Global Energy Model (DNE21)

- Hydrogen is consumed as a gaseous fuel alternative to natural gas, a fuel for hydrogen power gen. and for hydrogen FCV.
- Hydrogen can be converted into methanol and dimethyl ether (DME) in energy conversion plant, carbon monoxide by shift reaction.



<u>International Hydrogen Transport</u>

- Onshore: Pipeline
- Offshore: Tanker（Liquefied Hydrogen or MCH）

2-2. Key parameters (Production → Trasportation)

Technical assumptions on efficiency and cost of hydrogen production technologies

/1TOE Base Material	H_2 [TOE]	CO_2 [t-C]	Capital Cost [$/TOE/year]
Gas reformation	0.779	0.656	124.6
Coal oxidation	0.636	1.08	145
Oil oxidation	0.762	0.837	121.7
Biomass gasification	0.552	0.575	137.73
Water electrolysis	1.112	-	88.08

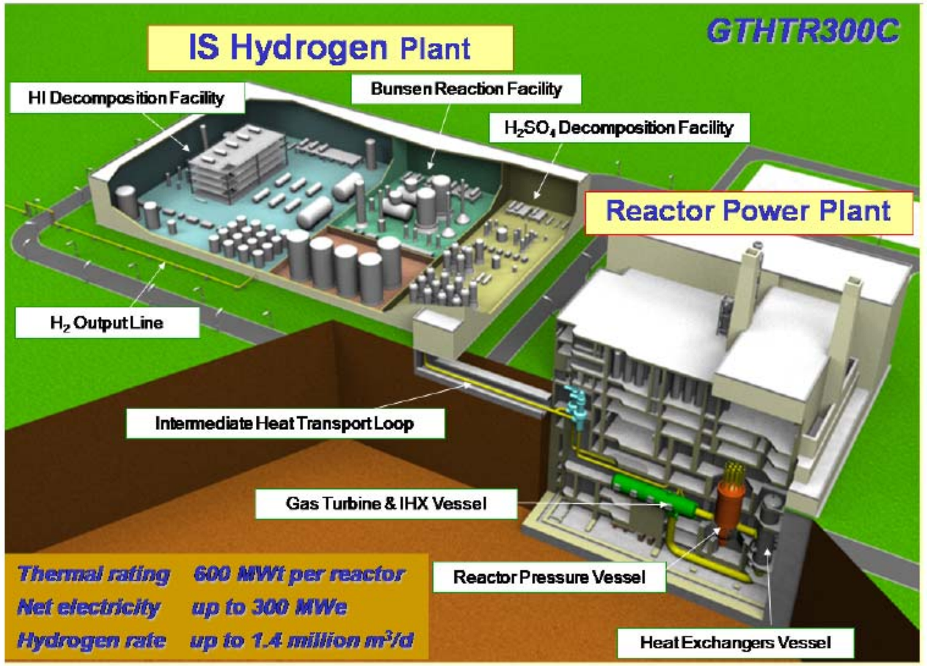
2-2. Key parameters (Production → Trasportation)

HTGR (High-temp. Gas Reactor)

- HTGR is considered as a co-generation plant producing both electricity and hydrogen.
- Supply and demand balance are considered in natural uranium, uranium 235, plutonium, spent fuels, and separating working in every region and time step.

		Unit	Value
HTGR Capital Cost		[$/kWe]	3635*
Burnup		[GWd/t]	120
Efficiency	Electricity	[%]	33.67
	Hydrogen	[%]	15.78
Fuel data of HTGR	(/1GWe)	Charged	Discharged
Uranium	[t/year]	7.22	5.814
U-235 concentration	[%]	14	4.5
Plutonium	[t/year]	0	0.168
Pu-fission rate	[%]	-	75.3
High level radioactive waste	[t/year]	0	0.445

* including hydrogen production plant.



(Source) JAEA

2-2. Key parameters (Production → Trasportation)

- Pipeline (onshore), liquid hydrogen tanker and methyl cyclohexane tanker (offshore) are considered in a detailed manner.
- Liquid hydrogen transportation additionally requires hydrogen liquefaction & gasification plants.

L =1000km	Fixed cost [$/TOE/Year]	Variable cost [$/TOE]
Pipeline(onshore)	28L	5.0L
Liquid hydrogen tanker (offshore)	13.9+8.50L	8.43+5.13L
Methyl cyclohexane tanker(offshore)	8.57+5.21L	4.28+2.61L

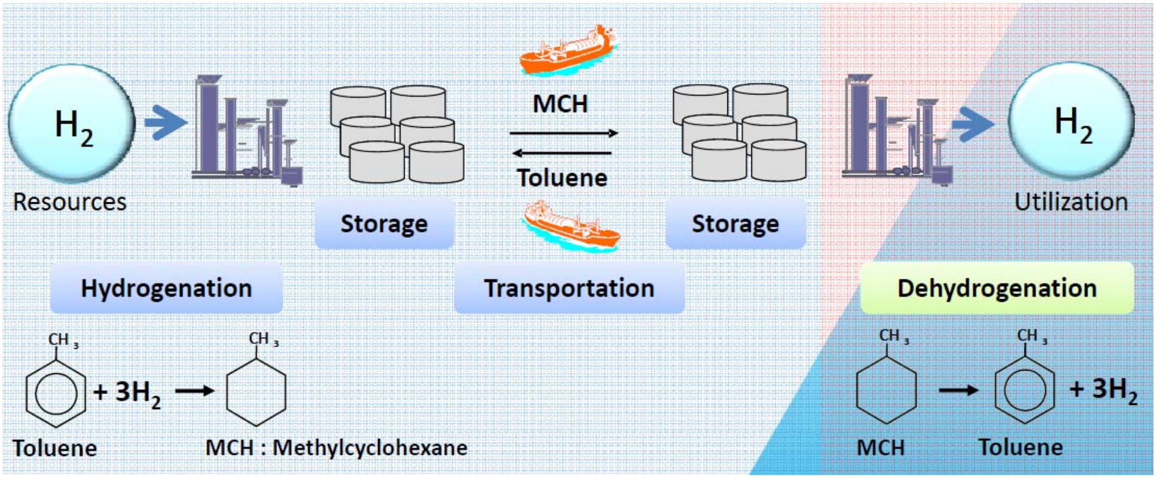
2-2. Key parameters (Production → Trasportation)

Methyl cyclohexane(MCH) tanker additionally requires hydrogenation & dehydrogenation plant.

Plant data for hydrogen transport through methylcyclohexane tanker

		Liquefaction	Gasification
Fixed cost	[$/TOE/year]	120.1	89.5
Variable cost	[$/TOE]	-	-
Electricity comsumption	[MWh/TOE]	3.329	0
loss rate	[%]	0	0

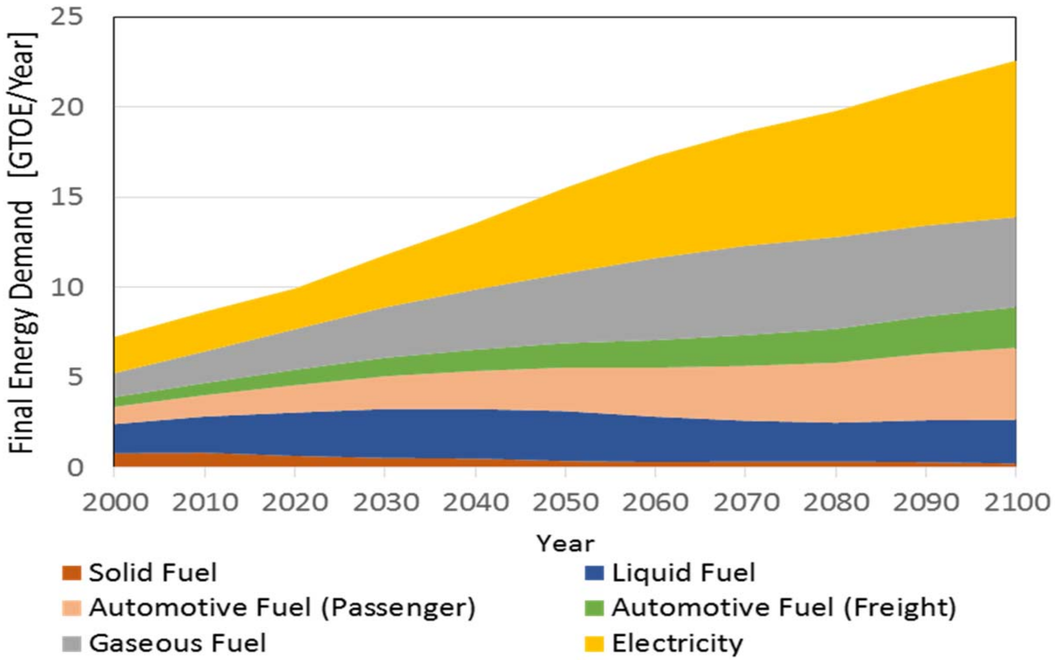
		Hydrogenation	Dehydrogenation
Fixed cost	[$/TOE/year]	64.8	144.63
Variable cost	[$/TOE]	0.27	2.1
Energy comsumption	-	0.04[MWh] (electricity)	0.2[TOE] (oil)
loss rate	[%]	2.15	10



(Source) Chiyoda Corporation

2-3. End-use Energy demand scenario

- Energy demand scenario is given exogenously based on reference to GEA (Global Energy Assessment) by IIASA (International Institute for Applied Systems Analysis).
- In order to represent the competition between several kinds of automotive fuel, liquid fuel demand is divided into automotive fuel demand and others.
- Moreover, automotive fuel demand is divided into passenger and freight usage.



2-4. Carbon regulation constraints

2°C Target Constraint

- CO_2 regulation is assumed to halve CO_2 emissions by the year 2050 for the world as a whole, and the emissions are constrained so that atmospheric CO_2 concentration is maintained at a level avoiding 2°C increase in the average global temperature from pre-industrial levels.

- Furthermore, the developed countries (high-income OECD countries) are assumed to reduce CO_2 emissions by 80% compared to the level in 2000 through 2050.

- This manuscript mainly explains the results in CO_2 REG case, although the results are calculated in business as usual (BAU) case as well in which CO_2 regulation is not assigned.

3. Results and Discussion

3-1. World

3-2. Sensitivity analysis on HTGR cost

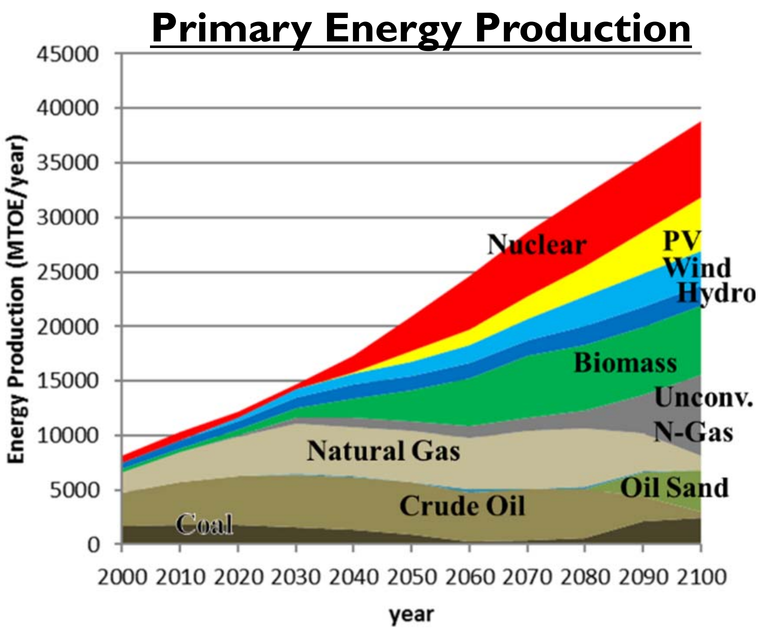
3-3. Western Europe

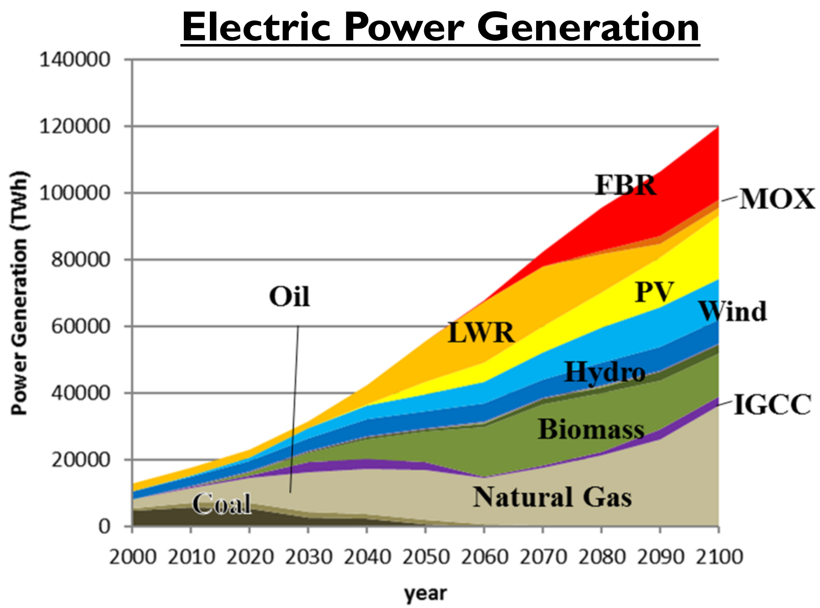
3-4. U.S.

3-5. Japan

3-1. Primary Energy Supply, Power Gen. Mix (World)

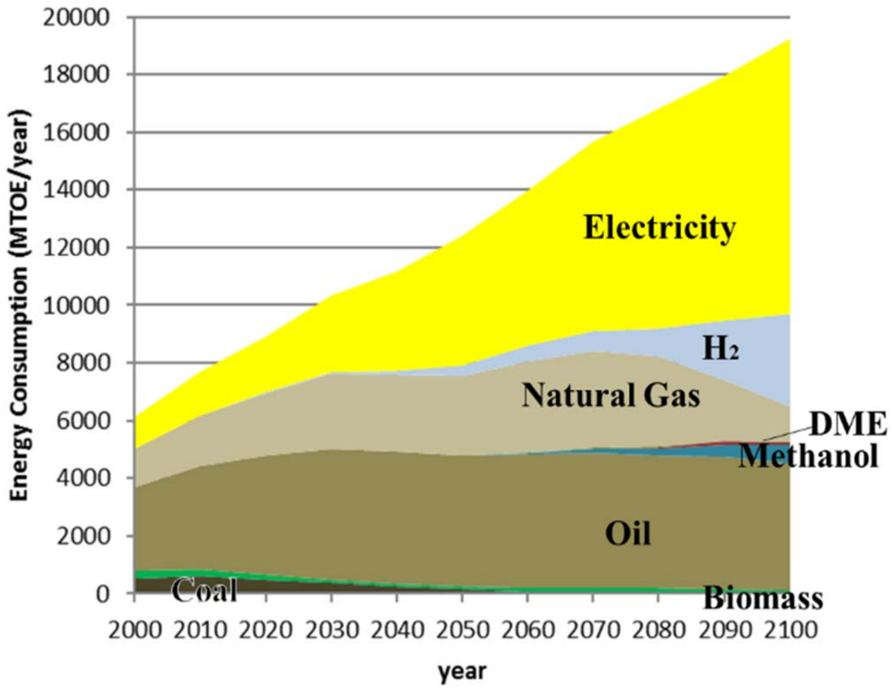
- Primary energy production:
  - Primary energy become decarbonized toward the end of the century by nuclear and renewable
- Electric power generation:
  - No single technology obtains dominant share
  - Nuclear (FBR), biomass, natural gas, PV and wind contribute to decarbonize power supply
  - Although thermal power plant with CCS shows significant growth later in the century, hydrogen power generation and HTGR co-generation do not appear in the result





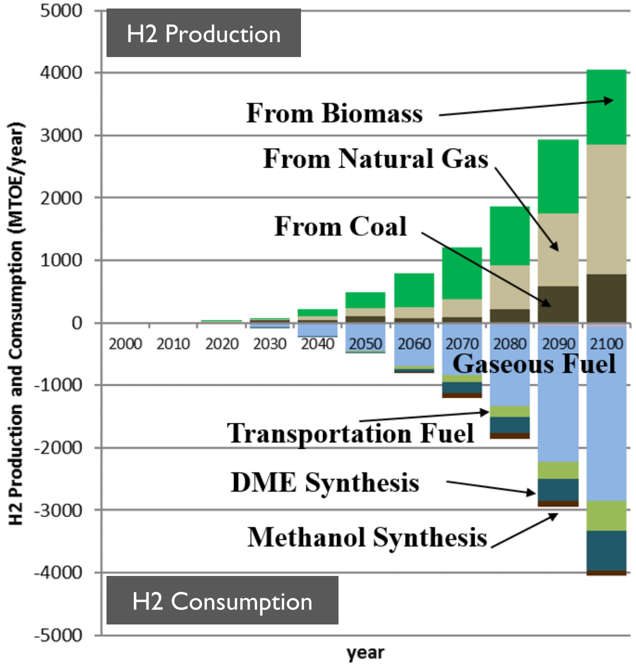
3-1. Final Energy Demand (World)

- From the mid-century, hydrogen starts to be penetrated, replacing the role of natural gas.
- Hydrogen, as an alternative fuel to natural gas, becomes economically viable carbon mitigation option.



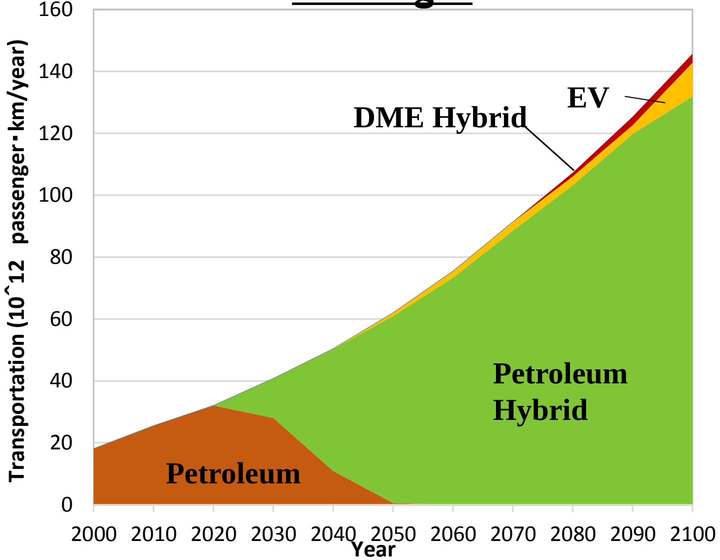
3-1. Hydrogen Demand and Supply Balance (World)

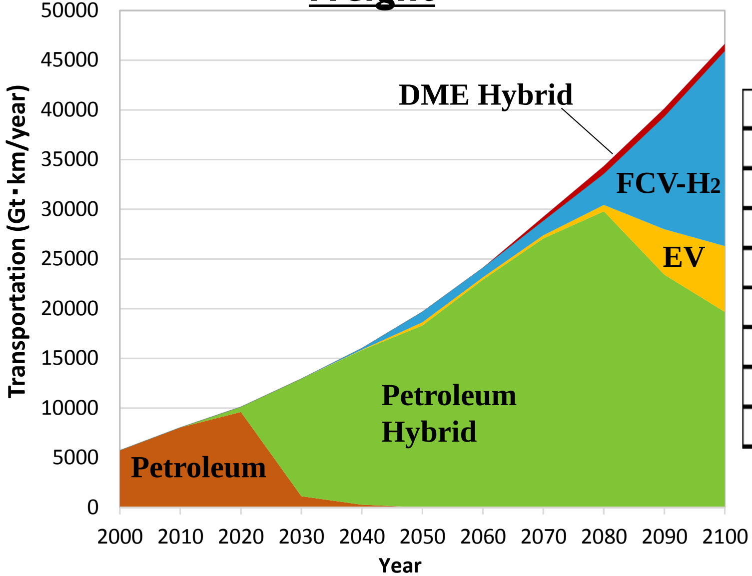
- Biomass remains main option for hydrogen production and mitigates carbon emissions.
- Hydrogen from natural gas and coal with CCS plays a significant role for the end of century.
- Hydrogen is mainly consumed as gaseous fuel, and in the end of the century, it comes to be used as transportation fuel as well.
- HTGR co-generation and hydrogen fuel power generation are not penetrated due to the costs.



3-1. Automobile Transportation (World)

- Fuel efficient vehicles such as HV and FCV play an important role, due to carbon restriction and the increase in oil production cost.
- In freight sector, EV and FCV become economically competitive later in the century. Annual mileage of freight vehicle is longer than that of passenger, and its capital recovery becomes faster.
- This study, however, does not consider the key parameters such as travel distance per one trip in each vehicle, limiting the detailed analysis of EV

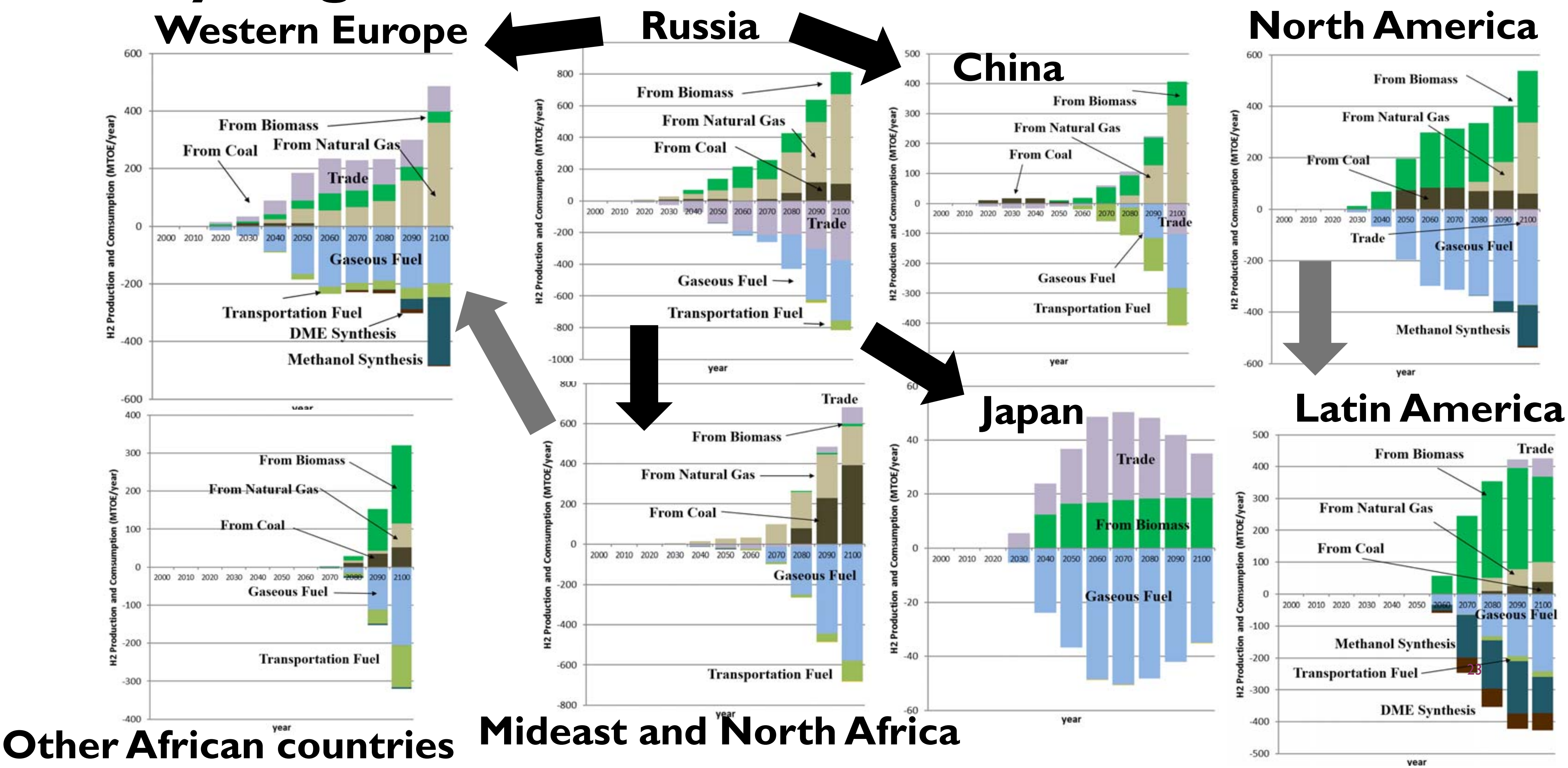




Fuel efficiency of conventional and advanced automobile technology

	2010	2050
Gasoline	1	1.2
Gasoline hydrid	1.525	2.15
Diesel	1.025	1.45
Diesel hybrid	1.625	2.275
Methanol,ethanol,DME	1	1.2
Methanol,ethanol,DME Hybrid	1.525	2.15
Electricity Vehicle	3.625	4.725
Hydrogen fuel cell	1.95	2.85

3-1. Hydrogen Trade of the world

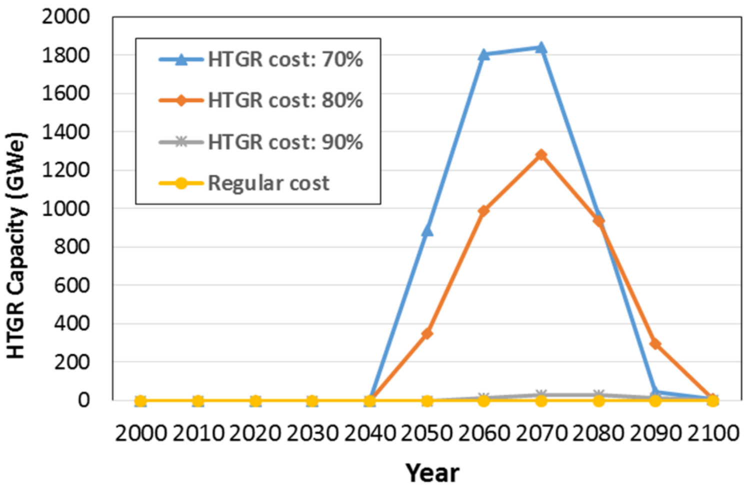


3-2. Sensitivity Analysis on HTGR Cost

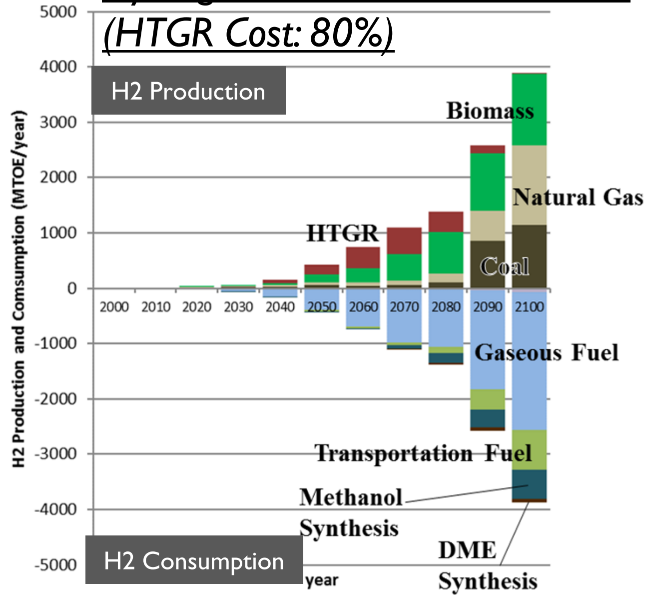
*HTGR: High Temperature Gas Reactor

- HTGR significantly penetrated once the cost get lower than 80% of reference cost.
- Hydrogen from HTGR is used as gaseous fuel and contributes to reduce carbon emissions.
- HTGR tends to be installed in the countries with less fossil fuel endowment.
- HTGR installation, however, decreases later in the century, due to the exhaustion of uranium resource.
- If plutonium-burning HTGR is considered, it might provide more sustainable hydrogen production than uranium-burning HTGR assumed in this paper

HTGR Capacity



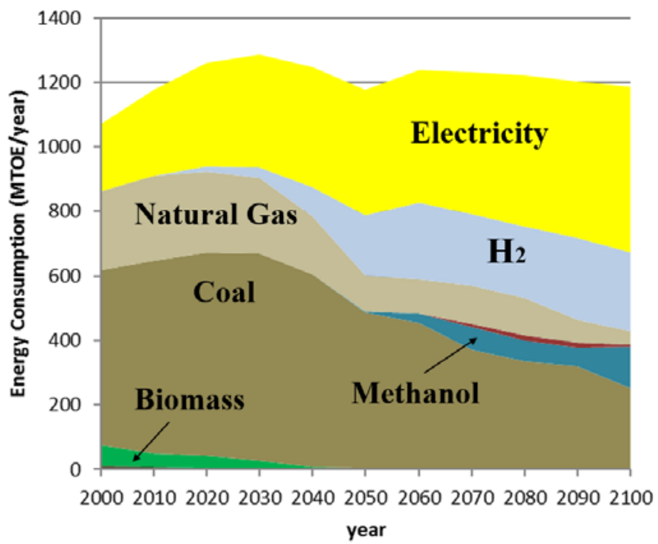
Hydrogen Production & Demand (HTGR Cost: 80%)



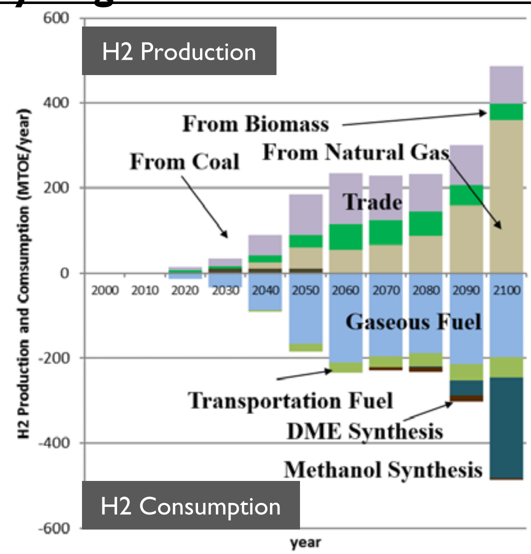
3-3. Western Europe

- In Western Europe, hydrogen has largely produced from fossil fuel or biomass with CCS after the mid-century when carbon regulation on OECD countries becomes severe.
- Hydrogen is transported through pipeline, not by a liquid hydrogen tanker or a methyl cyclohexane (MCH) tanker. Latter options cannot become an economically viable option in this study.
- Country with vast fossil fuel resource exports hydrogen to neighboring countries. W.U. import a great deal of hydrogen from Russia through pipeline. For countries with less fossil fuel endowment, the import of hydrogen might be relatively economical.
- Western Europe consumes hydrogen as gaseous fuel alternative to natural gas, a fuel for FCV and methanol synthesis.

Final Energy Demand



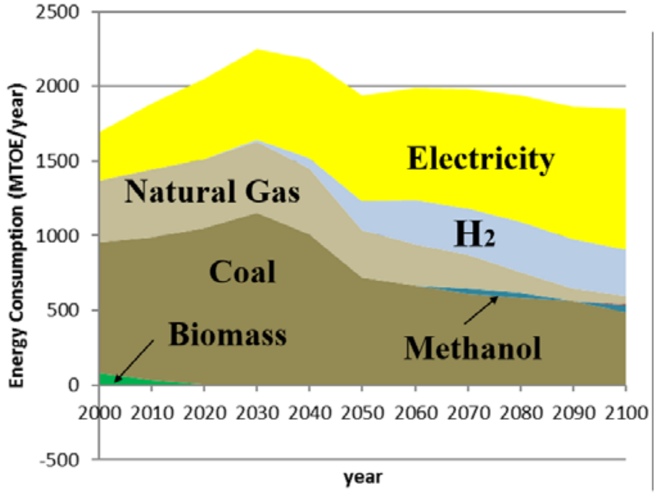
Hydrogen Production & Demand



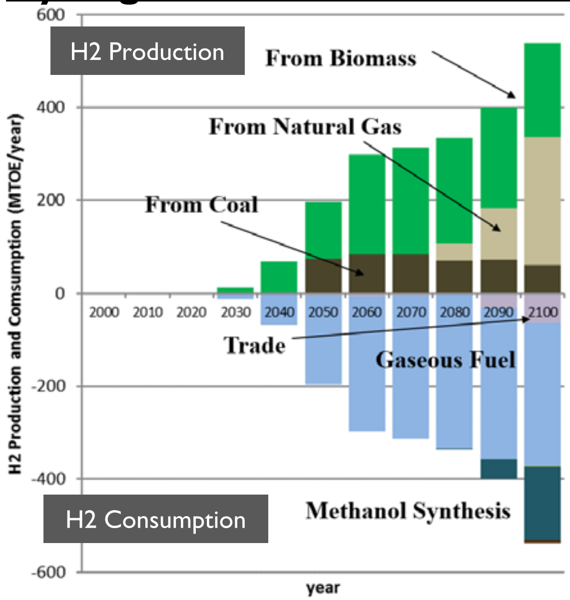
3-4. North America

- In North America as well, hydrogen has largely produced from fossil fuel and biomass with CCS after the mid-century.
- Countries such as USA with an abundance of natural gas or coal tend to be abundant of CCS potential such as coal mine and depleted gas well. Plentiful CCS potential allows the countries to economically produce hydrogen employing CCS.
- In North America, annual mileages of vehicles tend to be longer, hence fuel efficient vehicle such as hydrogen FCV is economically justified due to faster capital recovery.

Final Energy Demand



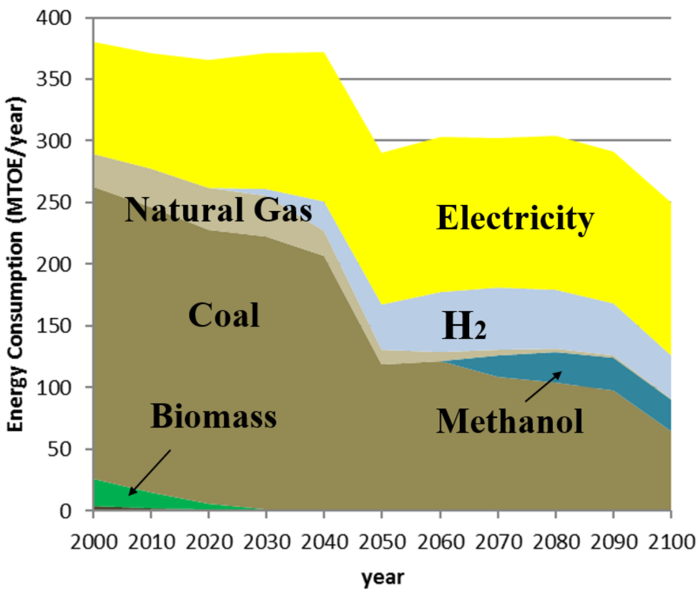
Hydrogen Production & Demand



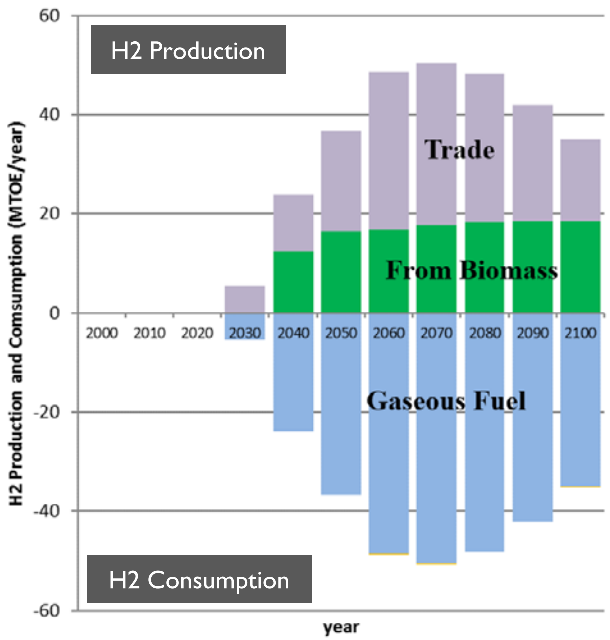
3-5. Japan

- In Japan, the majority of hydrogen is imported from Russia in the mid-century. After the mid-century, it has largely produced from biomass with CCS.
- It is difficult to produce hydrogen from fossil fuel in Japan because CCS potential is strictly limited.
- Almost all hydrogen is consumed as gaseous fuel.

Final Energy Demand



Hydrogen Production & Demand



4. Conclusion

- DNE21 is a model with detailed consideration of hydrogen to analyze its cost competitiveness under CO_2 regulation for 2 °C target

- Hydrogen production from fossil fuel and biomass with CCS would be one of economically viable carbon mitigation options for 2 °C target

- Hydrogen consumption as alternative gaseous fuel and fuel for FCV may become economically efficient under severe carbon regulation

- Concerning feasibility study on HTGR, future works are consideration on other reactor types such as plutonium-burning HTGR.

Thank you for your kind attention !

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東京大学 THE UNIVERSITY OF TOKYO

Appendix

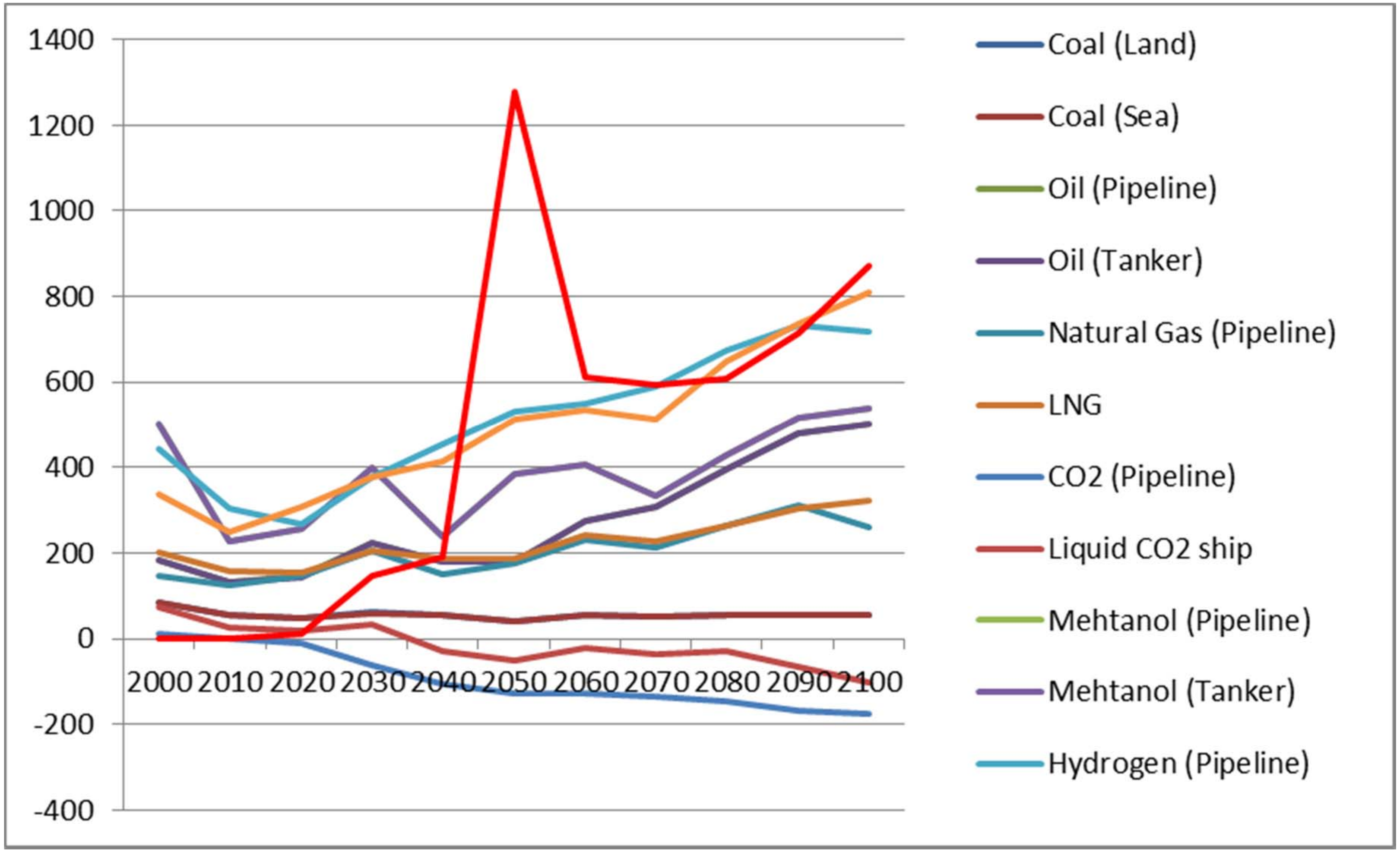
Hydrogen Transport Carrier

- MCH (Methylcyclohexane) (C_7H_{14}⇔C_7H_8) * Demonstration stage
  - ✓ (Advantage) higher H_2 density (500 times as much as gaseous H_2), availability in existing gasoline infrastructure
  - ✓ (Disadvantage) dehydrogenation (400℃ steam, energy loss (30%)), Bulky, need of H_2 refining for hydrogen station

- Liquefied Hydrogen * Commercialized in small-scale project
  - ✓ (Advantage) higher H_2 density (800 times as much as gaseous H_2), no need of H_2 refining for hydrogen station, commercialized in power generation (dual fuel at H_2 70%)
  - ✓ (Disadvantage) liquefaction(-253℃, energy loss (15%)), investment cost for infrastructure, boil-off (difficulty in long-term storage)

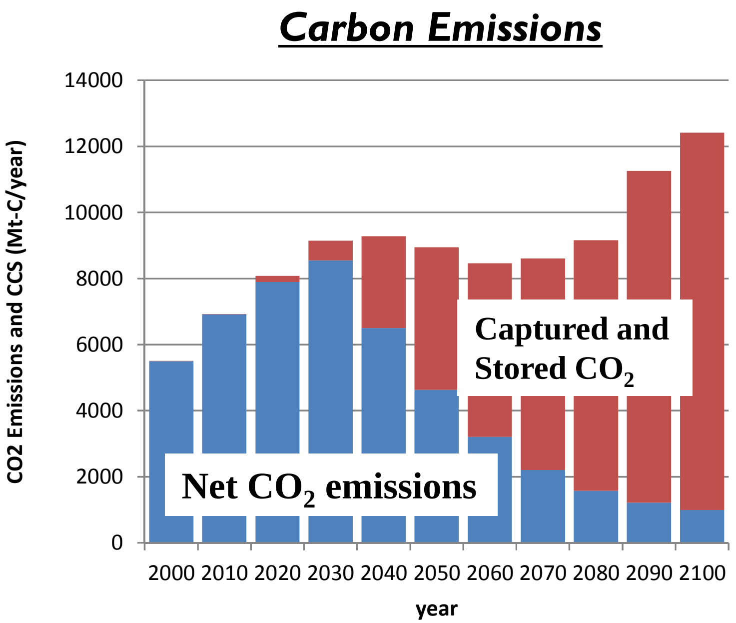
- Ammonia * R&D stage, Demonstration stage
  - ✓ (Advantage) higher H_2 density (1200 times as much as gaseous H_2(-33℃ or 8Pa)), availability in existing LPG infrastructure, direct combustion in FC (fuel cell), cheap cost
  - ✓ (Disadvantage) toxicity, energy loss in dehydrogenation, need of H_2 refining for hydrogen station

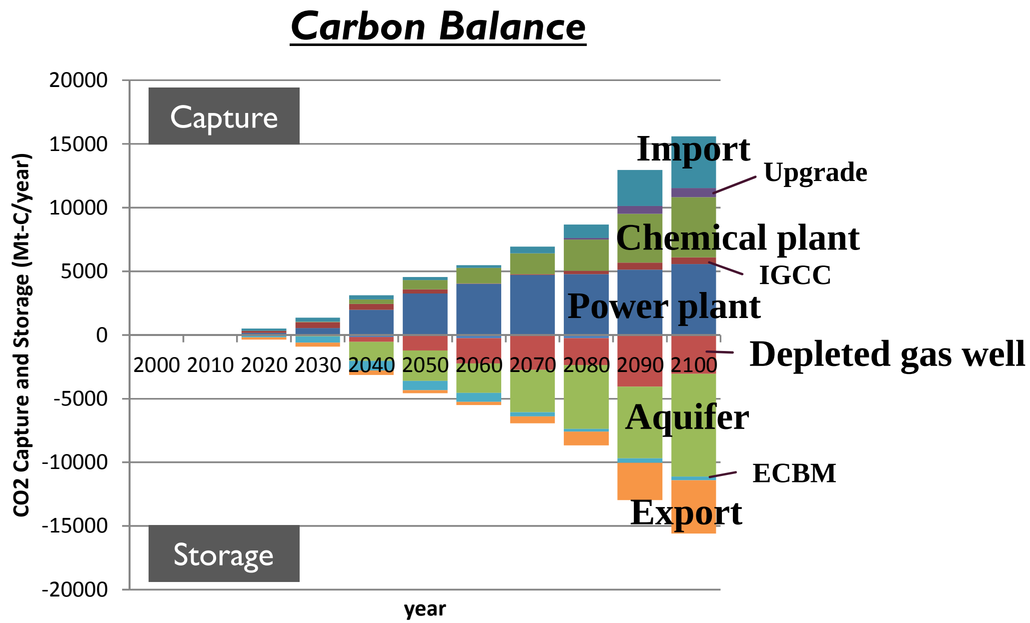
Shadow Price (World)



Carbon Emissions (World)

- 90% of carbon emissions are captured and sequestrated in the end of the century.
- Carbon emissions are mainly captured in power plants and chemical plants and are stored in aquifer and depleted gas well.

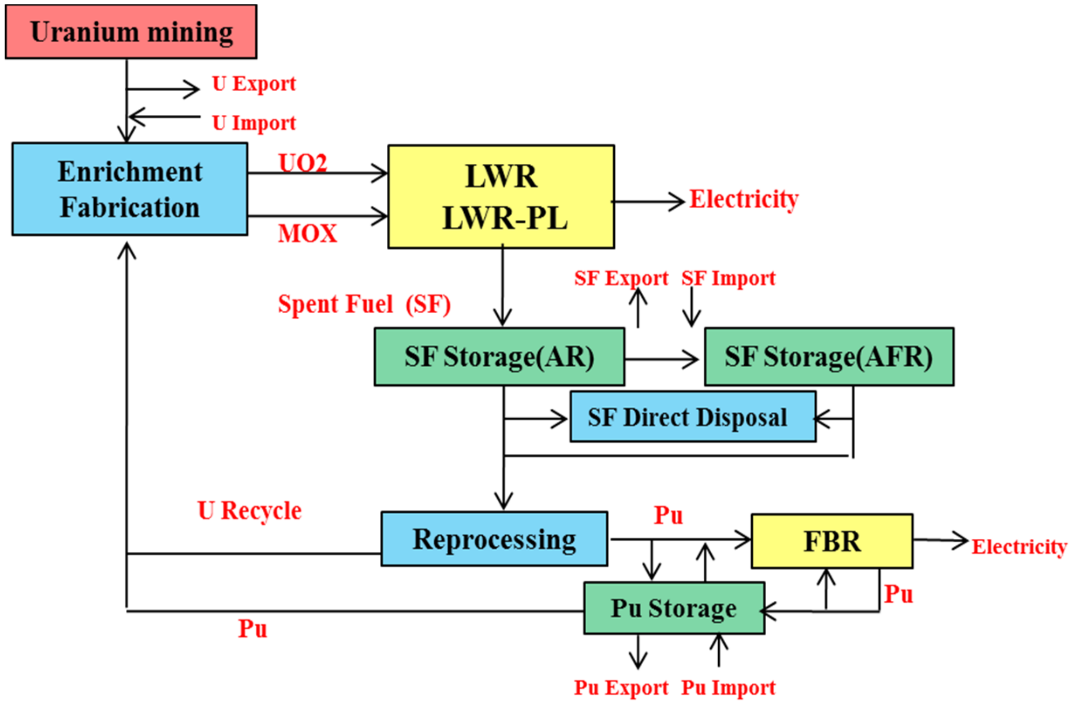




Global Energy Model (DNE21)

Nuclear Fuel Cycle Module

- Isotopic composition of uranium and plutonium is considered in a detailed manner.



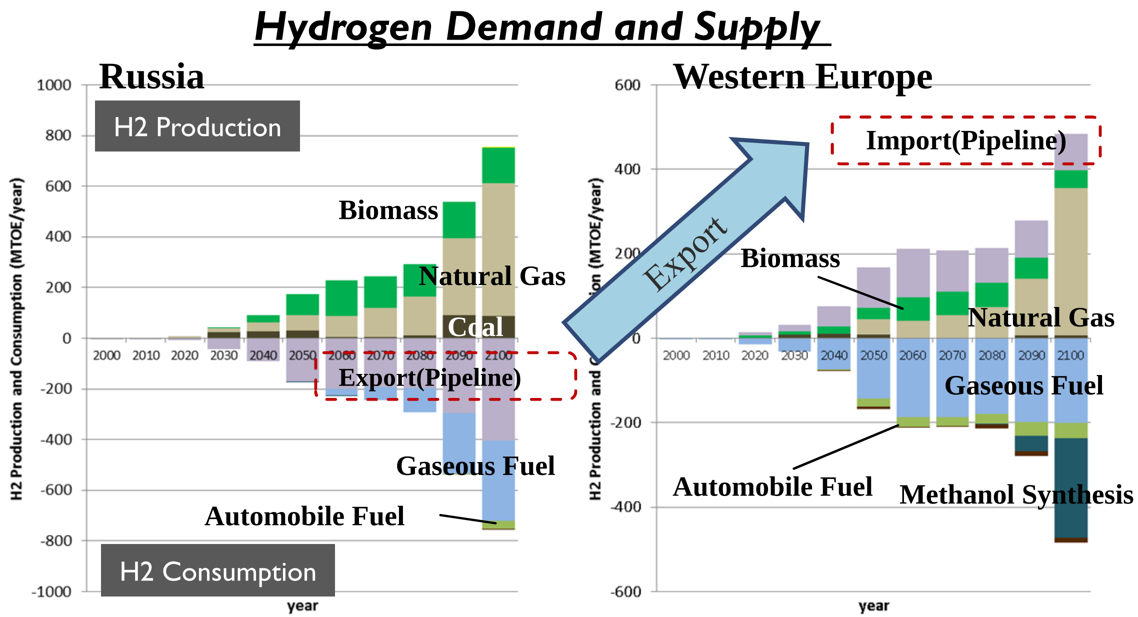
2-2. Key parameters (Production Trasportation Consumpt
Automobile Technology

Fuel efficiency of conventional and advanced automobile technology (normalized to gasoline passenger vehicle in 2000)

	2010	2050
Gasoline	1	1.2
Gasoline hydrid	1.525	2.15
Diesel	1.025	1.45
Diesel hybrid	1.625	2.275
Methanol,ethanol,DME	1	1.2
Methanol,ethanol,DME Hybrid	1.525	2.15
Electricity Vehicle	3.625	4.725
Hydrogen fuel cell	1.95	2.85

Hydrogen Trade (Russia-Western Europe)

- Western EU imports hydrogen through pipeline from Russia (as well in Japan)
- In Russia, hydrogen is produced from natural gas reformation with CCS.
- Globally, MCH and liquefied hydrogen tanker are not selected as hydrogen transport technology, due to its massive investment cost



Hydrogen Trade (Russia-Western Europe)

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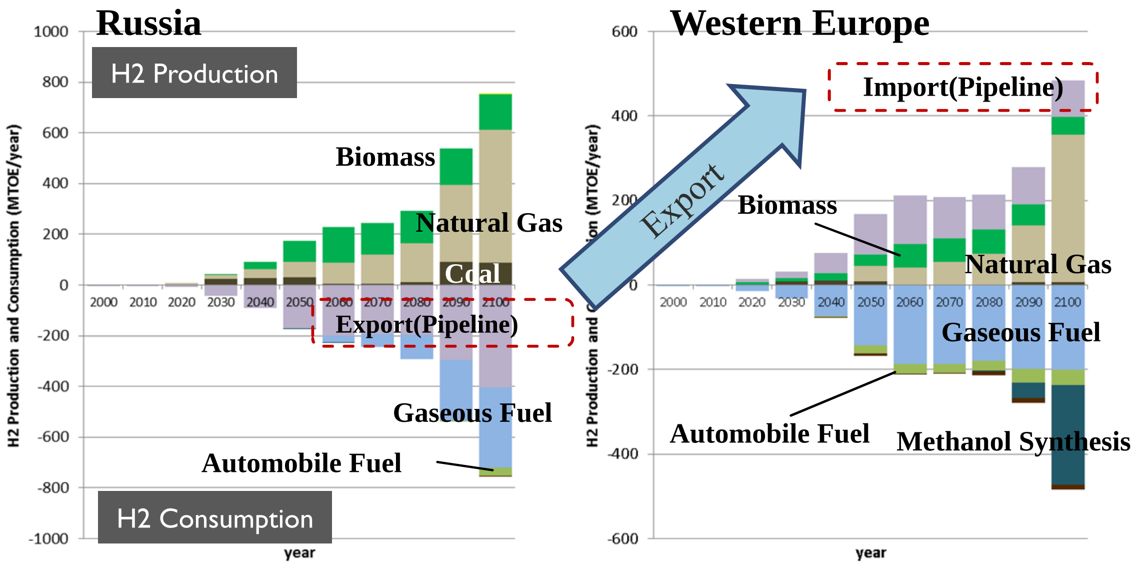
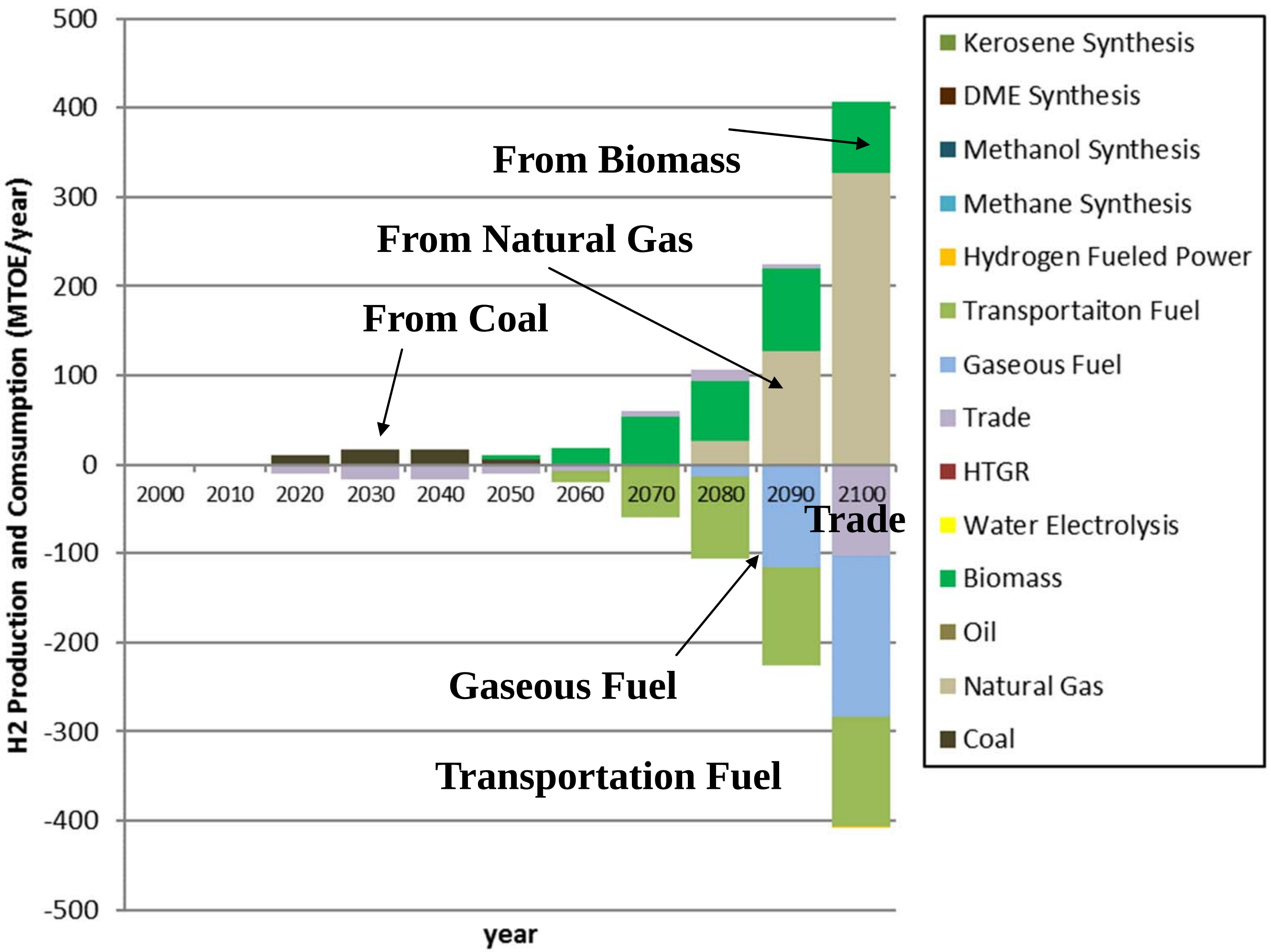
Hydrogen Demand and Supply





500
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300
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100
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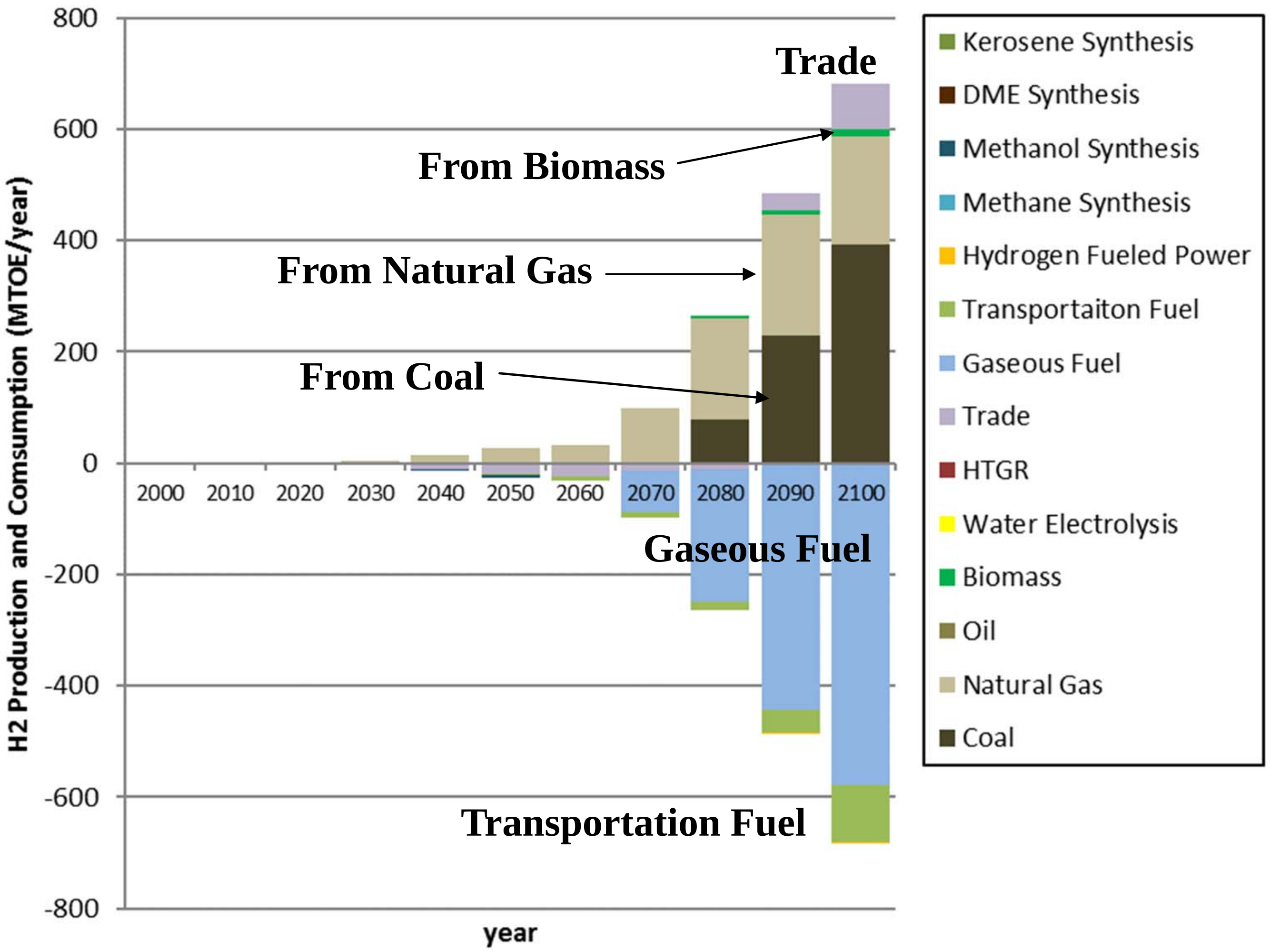
-100
-200
-300
-400
-500
H2 Production and Comsumption (MTOE/year)
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
year
From Biomass
From Natural Gas
From Coal
Trade
Gaseous Fuel
Transportation Fuel
Kerosene Synthesis
DME Synthesis
Methanol Synthesis
Methane Synthesis
Hydrogen Fueled Power
Transportaiton Fuel
Gaseous Fuel
Trade
HTGR
Water Electrolysis
Biomass
Oil
Natural Gas
Coal



800
600
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0
-200
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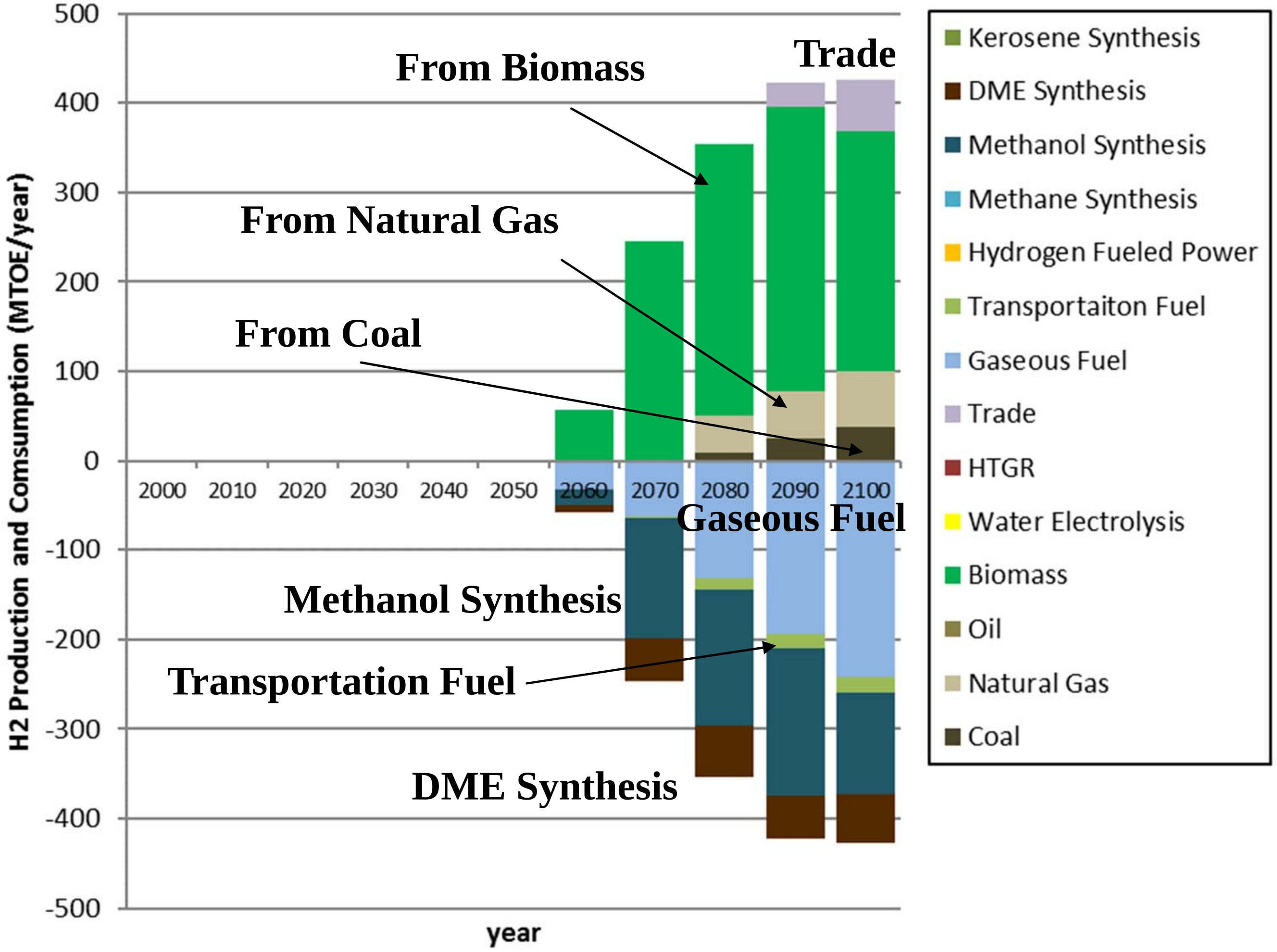
-600
-800
H2 Production and Comsumption (MTOE/year)
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
year
Trade
From Biomass
From Natural Gas
From Coal
Gaseous Fuel
Transportation Fuel
Kerosene Synthesis
DME Synthesis
Methanol Synthesis
Methane Synthesis
Hydrogen Fueled Power
Transportaiton Fuel
Gaseous Fuel
Trade
HTGR
Water Electrolysis
Biomass
Oil
Natural Gas
Coal


From Biomass
Trade
From Natural Gas
From Coal
Gaseous Fuel
Methanol Synthesis
Transportation Fuel
DME Synthesis
H2 Production and Comsumption (MTOE/year)
year
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300
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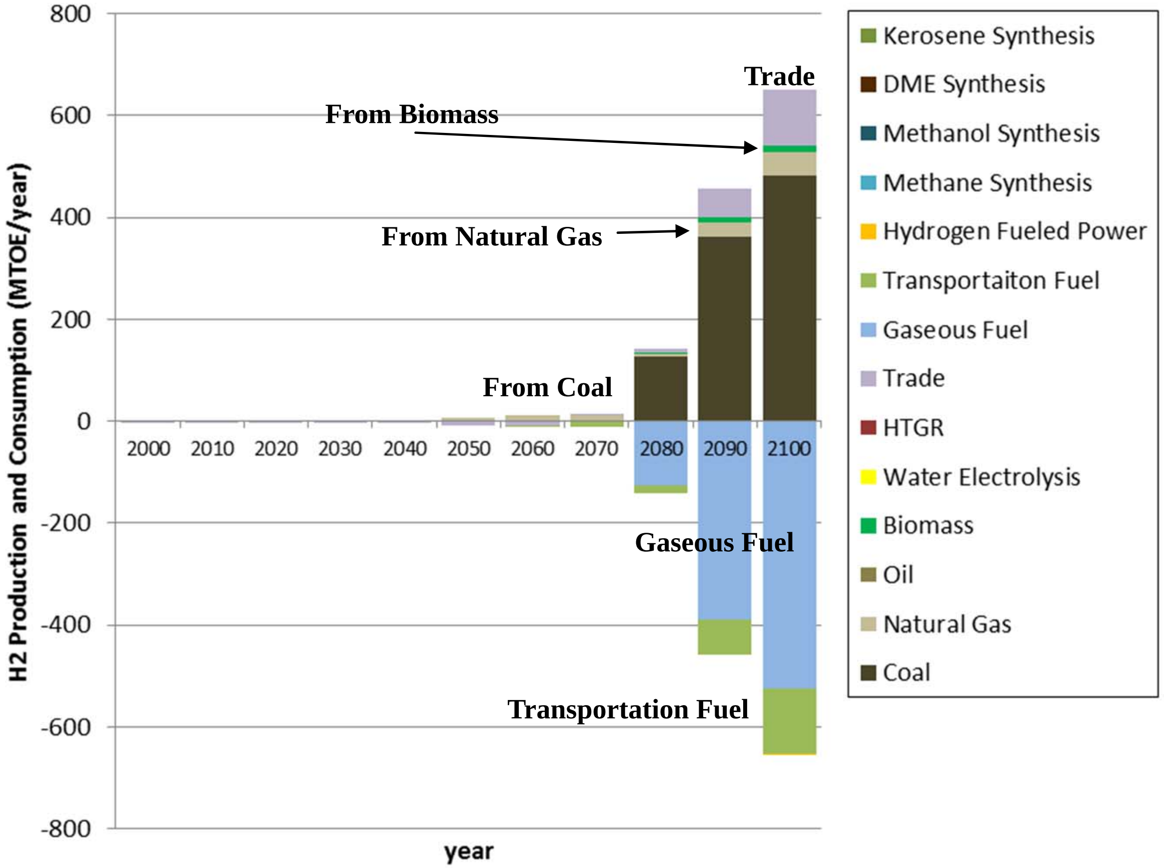
Kerosene Synthesis
DME Synthesis
Methanol Synthesis
Methane Synthesis
Hydrogen Fueled Power
Transportaiton Fuel
Gaseous Fuel
Trade
HTGR
Water Electrolysis
Biomass
Oil
Natural Gas
Coal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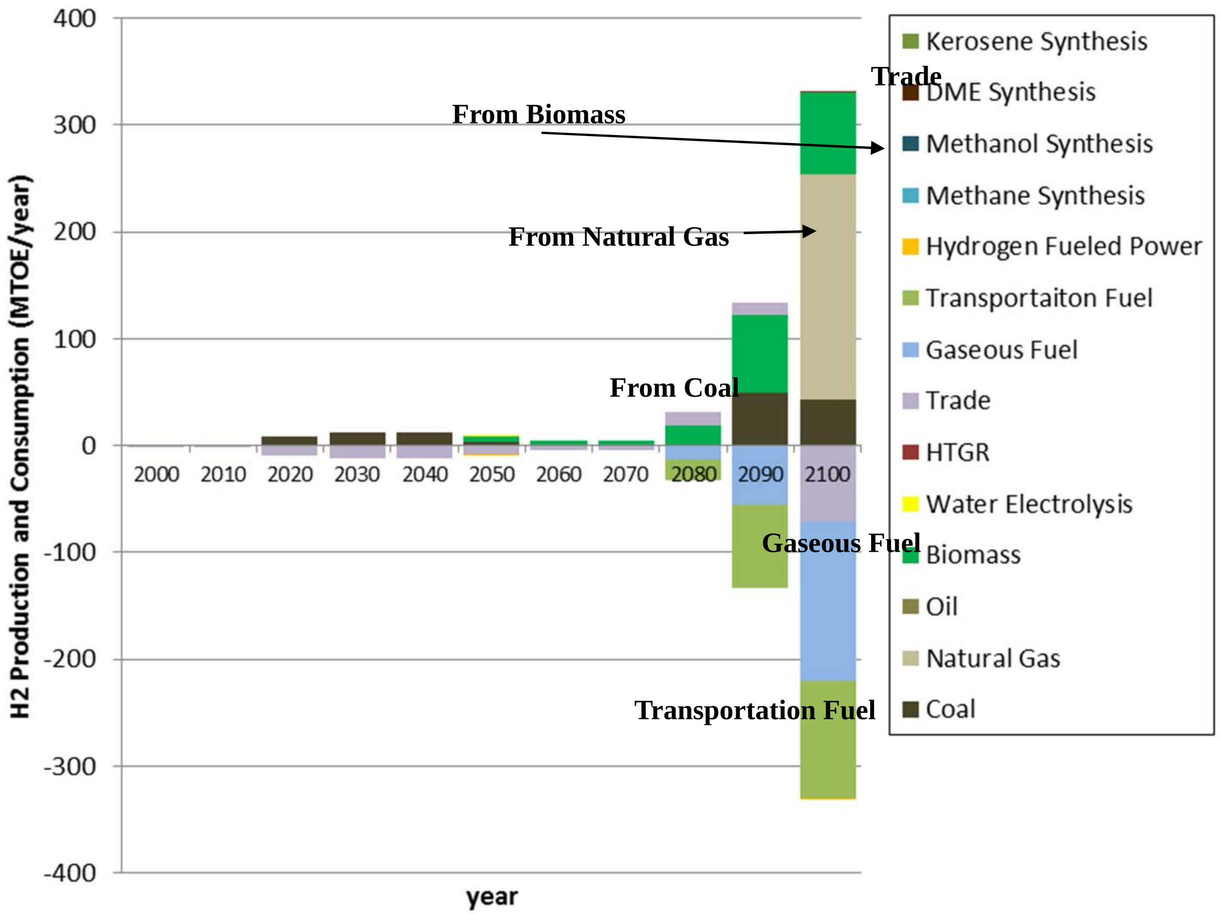
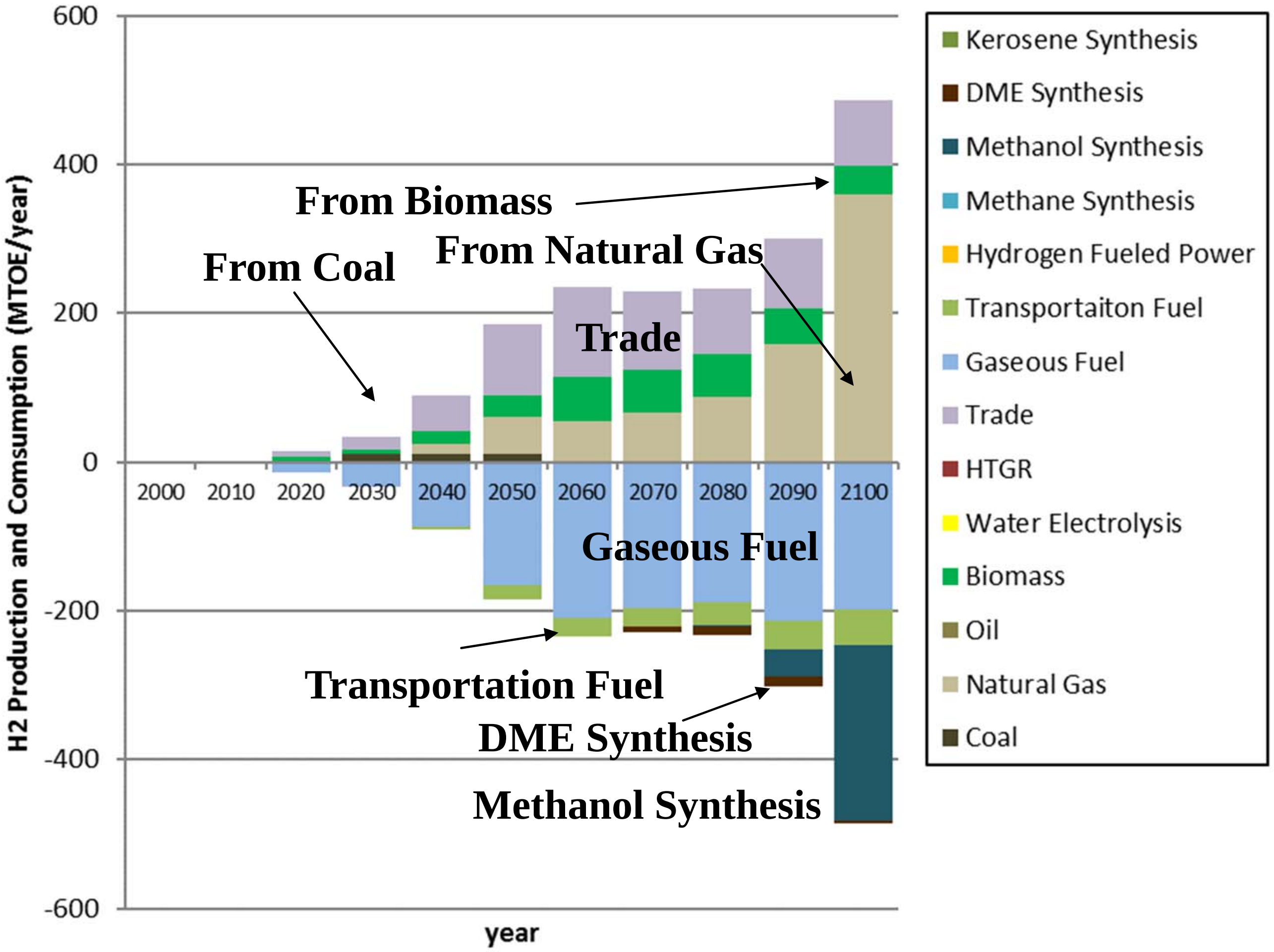
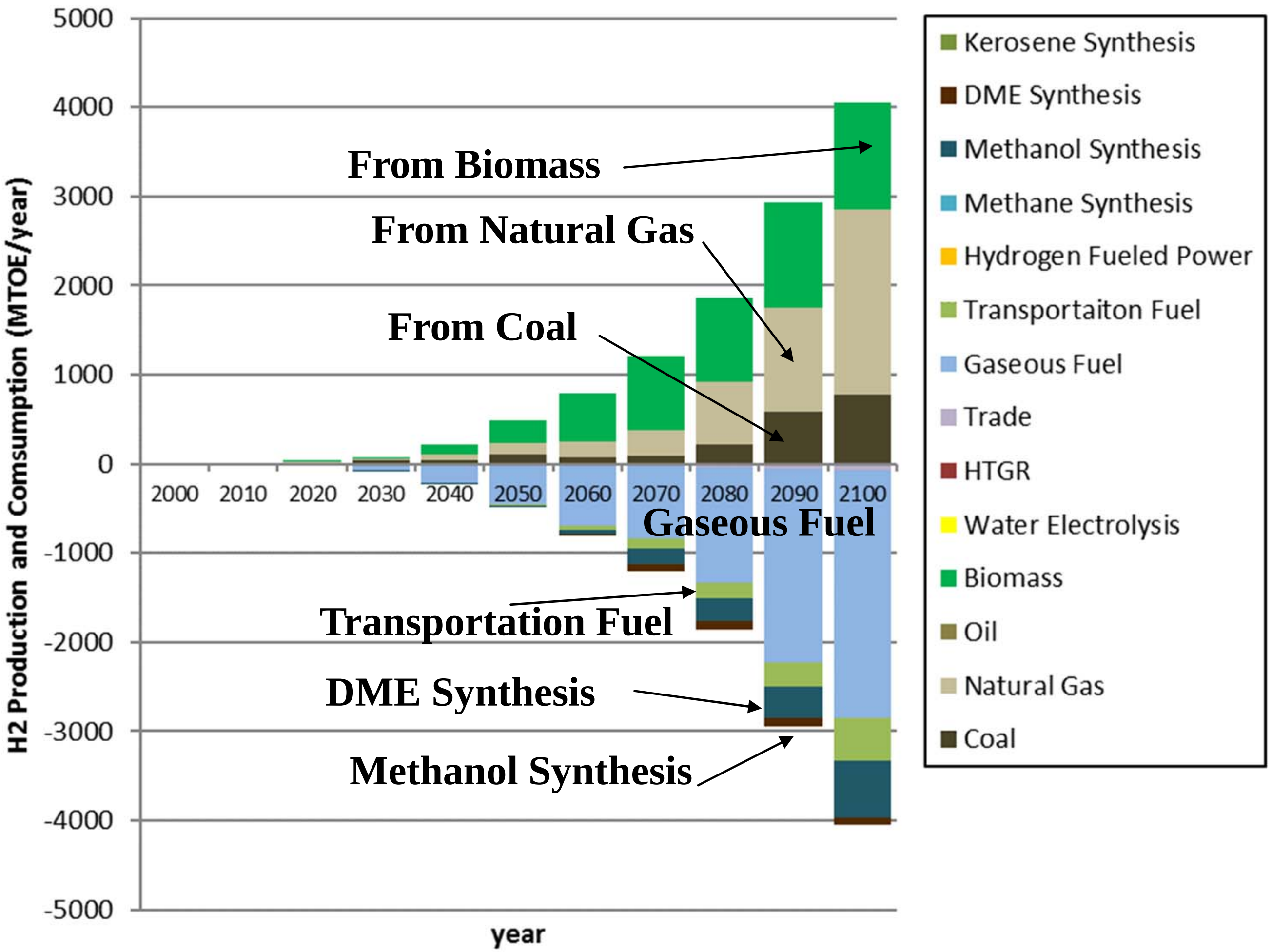
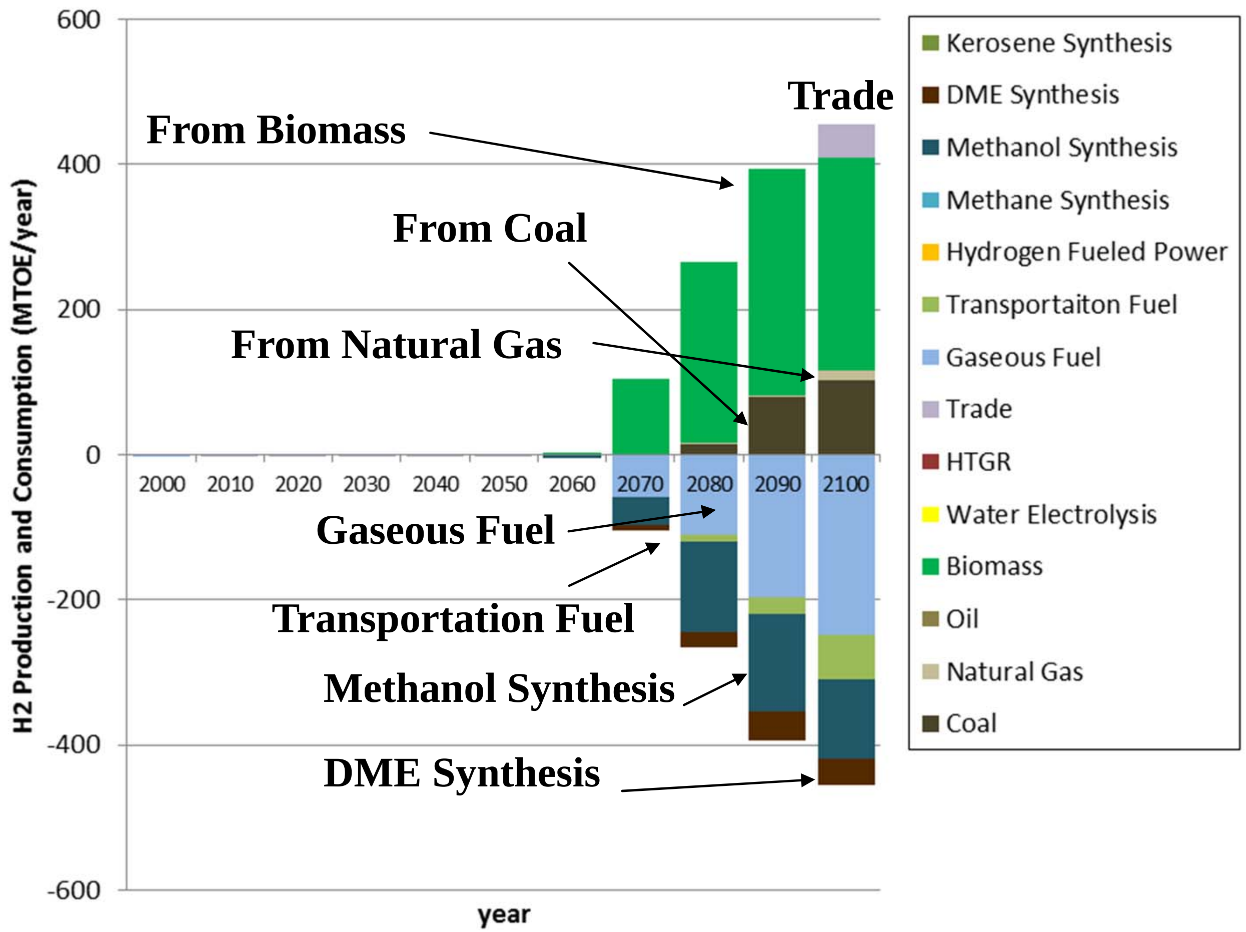
-800
H2 Production and Consumption (MTOE/year)
year
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Trade
From Biomass
From Natural Gas
From Coal
Gaseous Fuel
Transportation Fuel
Kerosene Synthesis
DME Synthesis
Methanol Synthesis
Methane Synthesis
Hydrogen Fueled Power
Transportaiton Fuel
Gaseous Fuel
Trade
HTGR
Water Electrolysis
Biomass
Oil
Natural Gas
Coal

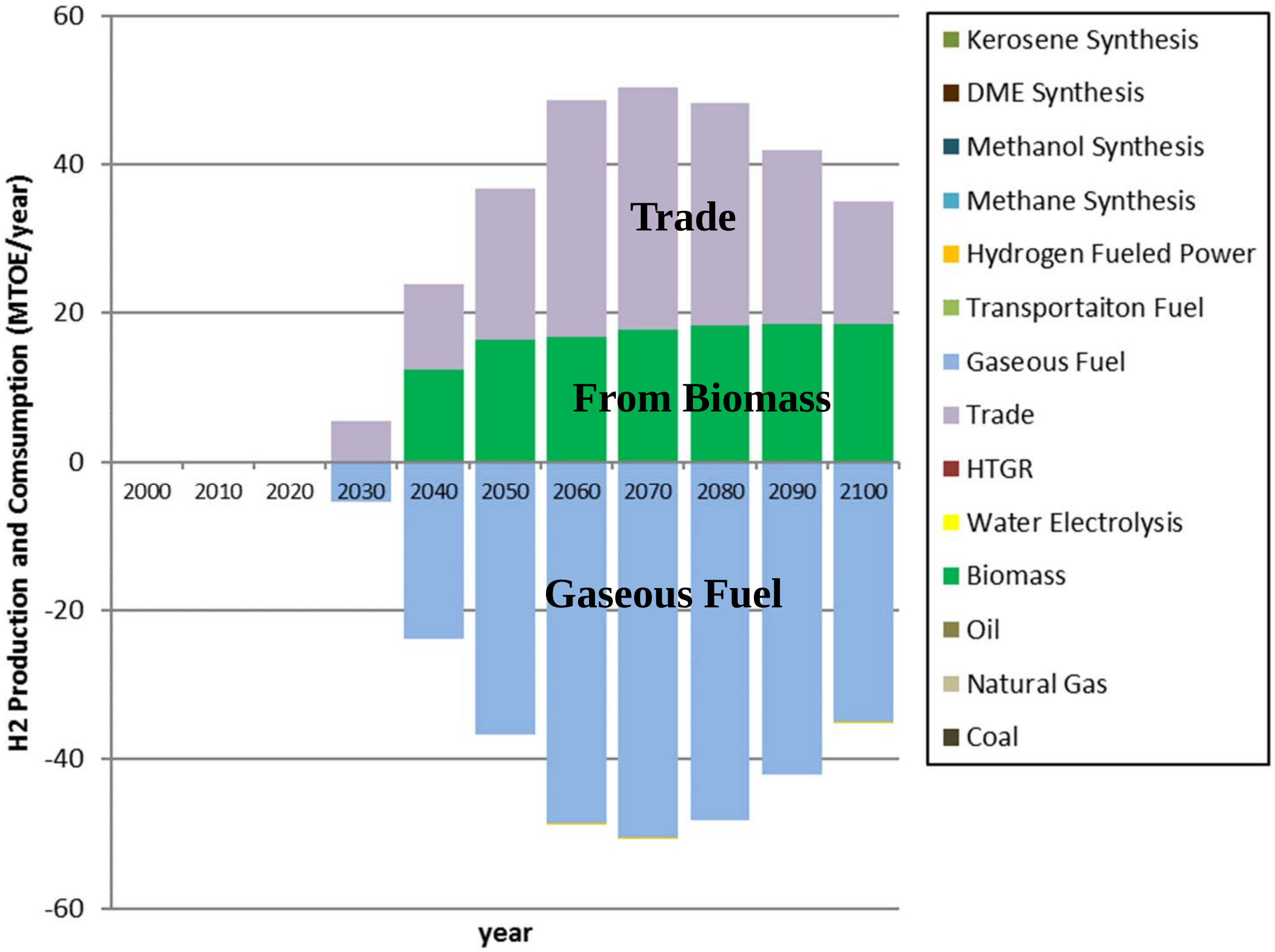

400
300
200
100
0
-100
-200
-300
-400
H2 Production and Consumption (MTOE/year)
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
year
From Biomass
From Natural Gas
From Coal
Trade
Gaseous Fuel
Transportation Fuel
Kerosene Synthesis
DME Synthesis
Methanol Synthesis
Methane Synthesis
Hydrogen Fueled Power
Transportaiton Fuel
Gaseous Fuel
Trade
HTGR
Water Electrolysis
Biomass
Oil
Natural Gas
Coal


600
400
200
0
-200
-400
-600
H2 Production and Comsumption (MTOE/year)
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
year
From Biomass
From Coal
From Natural Gas
Trade
Gaseous Fuel
Transportation Fuel
DME Synthesis
Methanol Synthesis
Kerosene Synthesis
DME Synthesis
Methanol Synthesis
Methane Synthesis
Hydrogen Fueled Power
Transportaiton Fuel
Gaseous Fuel
Trade
HTGR
Water Electrolysis
Biomass
Oil
Natural Gas
Coal

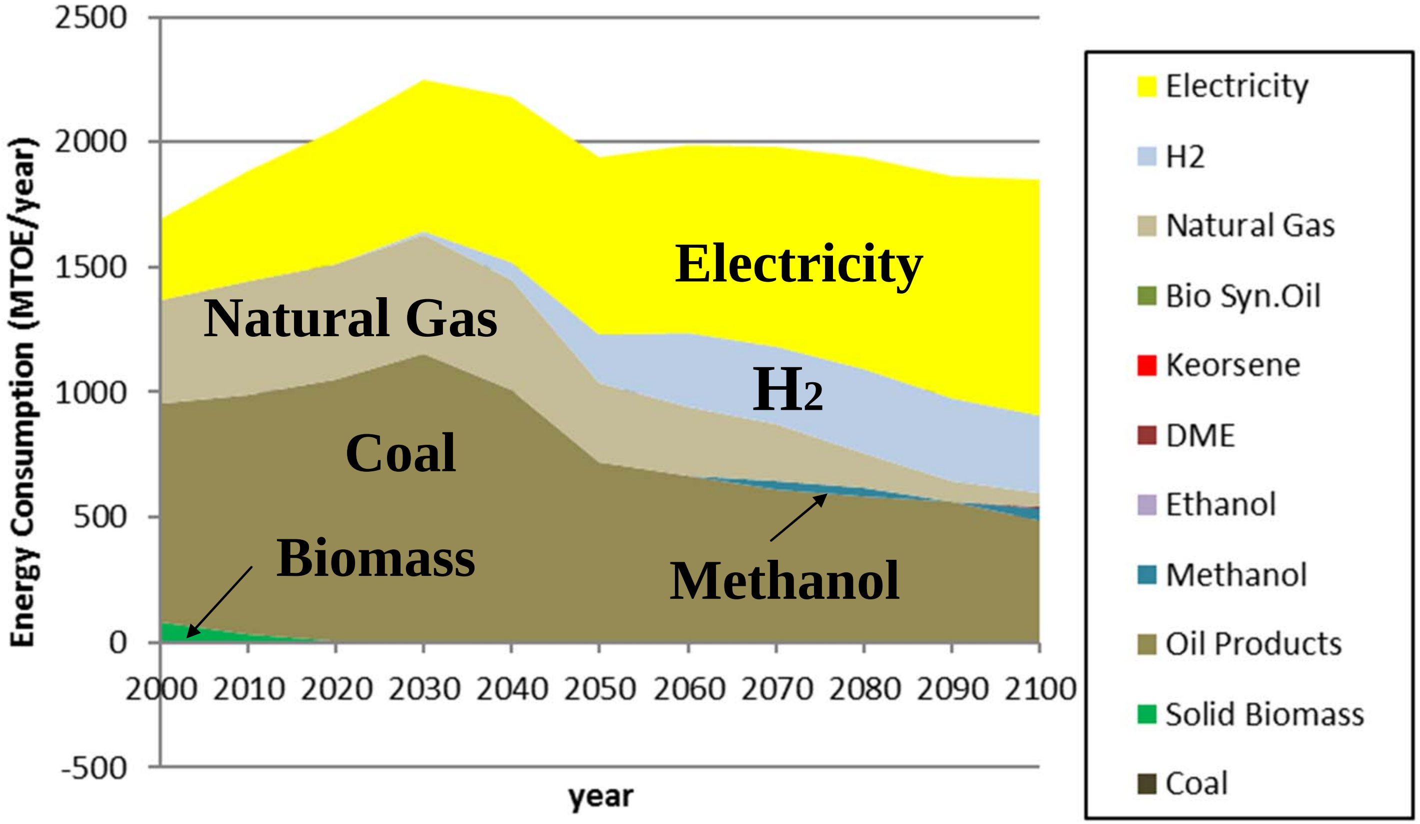


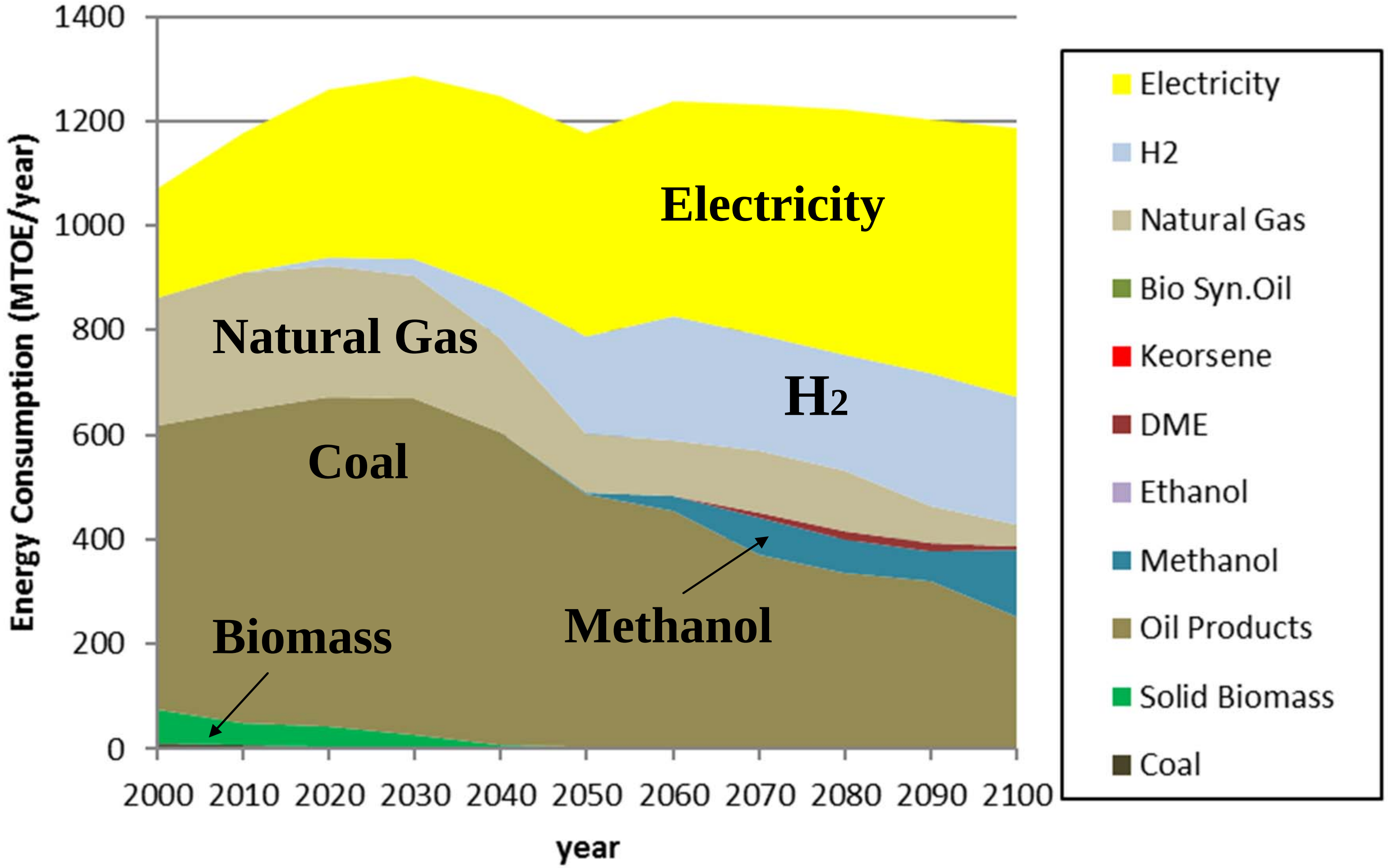
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
H2 Production and Comsumption (MTOE/year)
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
year
From Biomass
From Natural Gas
From Coal
Gaseous Fuel
Transportation Fuel
DME Synthesis
Methanol Synthesis
Kerosene Synthesis
DME Synthesis
Methanol Synthesis
Methane Synthesis
Hydrogen Fueled Power
Transportaiton Fuel
Gaseous Fuel
Trade
HTGR
Water Electrolysis
Biomass
Oil
Natural Gas
Coal


600
400
200
0
-200
-400
-600
H2 Production and Consumption (MTOE/year)
year
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
From Biomass
From Coal
From Natural Gas
Trade
Gaseous Fuel
Transportation Fuel
Methanol Synthesis
DME Synthesis
Kerosene Synthesis
DME Synthesis
Methanol Synthesis
Methane Synthesis
Hydrogen Fueled Power
Transportaiton Fuel
Gaseous Fuel
Trade
HTGR
Water Electrolysis
Biomass
Oil
Natural Gas
Coal



60
40
20
0
-20
-40
-60
H2 Production and Comsumption (MTOE/year)
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
year
Trade
From Biomass
Gaseous Fuel
Kerosene Synthesis
DME Synthesis
Methanol Synthesis
Methane Synthesis
Hydrogen Fueled Power
Transportaiton Fuel
Gaseous Fuel
Trade
HTGR
Water Electrolysis
Biomass
Oil
Natural Gas
Coal


2500
2000
1500
1000
500
0
-500
Energy Consumption (MTOE/year)
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
year
Electricity
Natural Gas
H2
Coal
Biomass
Methanol
Electricity
H2
Natural Gas
Bio Syn.Oil
Keorsene
DME
Ethanol
Methanol
Oil Products
Solid Biomass
Coal



Electricity
Natural Gas
H2
Coal
Biomass
Methanol
1400
1200
1000
800
600
400
200
0
Energy Consumption (MTOE/year)
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
year
Electricity
H2
Natural Gas
Bio Syn.Oil
Keorsene
DME
Ethanol
Methanol
Oil Products
Solid Biomass
Coal

3-1. Final Energy Demand (World)