



Exploring the Cost-Effective Strategy for Introducing Hydrogen by Considering Hydrogen Supply Infrastructure in Detail

International Energy Workshop 2009
Fondazione Giorgio Cini, Venice, Italy, June 17-19, 2009

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Outline

- Introduction
 - Background
 - Research objective
- Methodology
 - Model structure
 - Assumptions and data
- Results and discussion
 - Competitiveness of hydrogen under a 400 ppmv CO₂ stabilization constraint
 - Cost-effective strategy for producing, transporting, and using hydrogen under the CO₂ stabilization constraint
- Summary

Introduction

- **Research background**

- The development of hydrogen supply infrastructure is often seen as a significant economic barrier to the widespread use of hydrogen.
- The pace of solving the problems associated with fuel cell systems and hydrogen on-board storage is more slow than was anticipated.
- CO₂ mitigation technologies using electricity, such as heat pumps and plug-in hybrid vehicles, have advanced steadily.
- Some researchers raise question about future prospects of hydrogen.

- **Research objective**

- To assess the economic competitiveness of hydrogen under a 400 ppmv CO₂ stabilization constraint
- To derive the cost-effective strategy for producing, transporting, and using hydrogen under the CO₂ stabilization constraint
- These analyses are performed using a global energy system model that treats hydrogen supply infrastructure, hydrogen utilization technologies, and competing technologies in detail

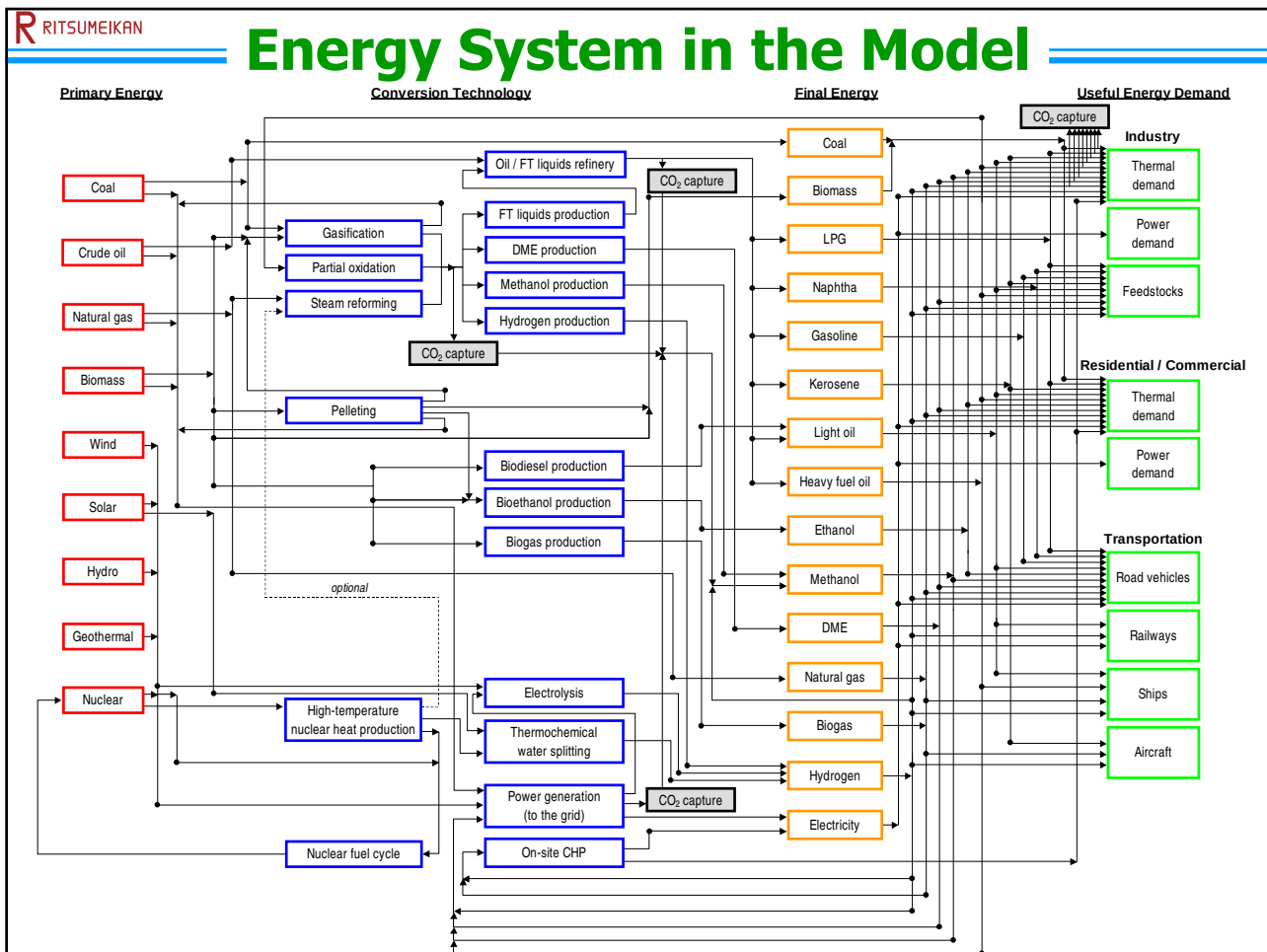
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Overview of the Model Used

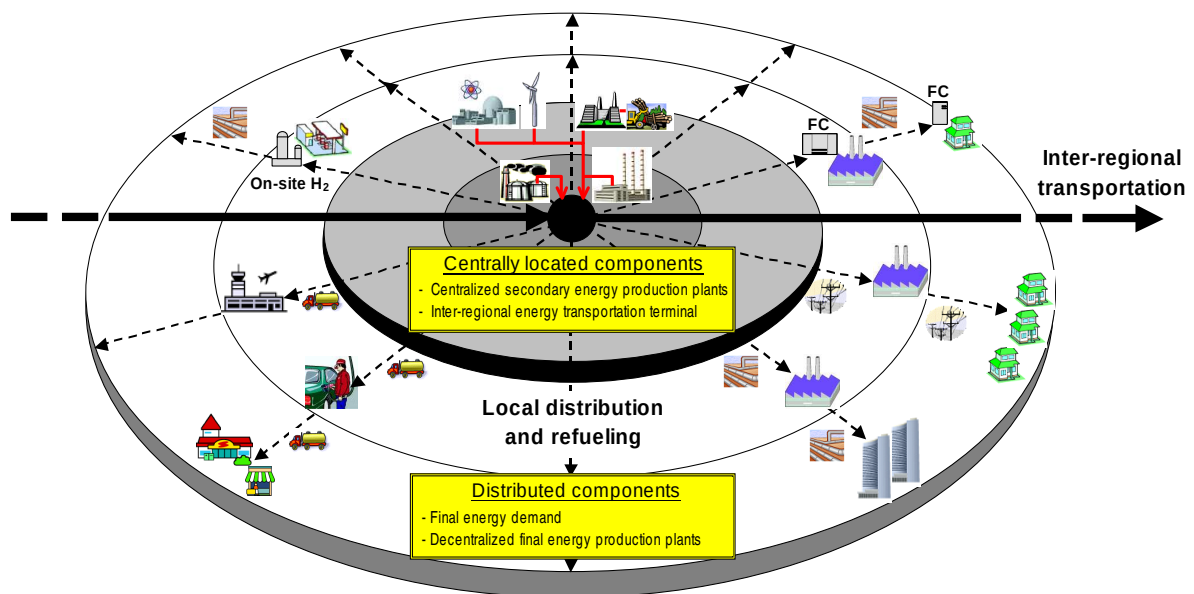
- Bottom-up type global energy systems optimization model designed to determine the optimal mix of technology options from 2000 to 2100 at 10-year intervals
- Detailed regional disaggregation (the whole world being divided into 70 regions) enabling
 - Explicit consideration of the regional characteristics
 - Treatment of the interregional transportation of energy and CO₂
- Detailed representation of the spatial structure of each world region by consideration of the distribution of energy system components
- Future socio-economic driving forces based on the IIASA-WEC study's middle-course Case B

Energy System in the Model



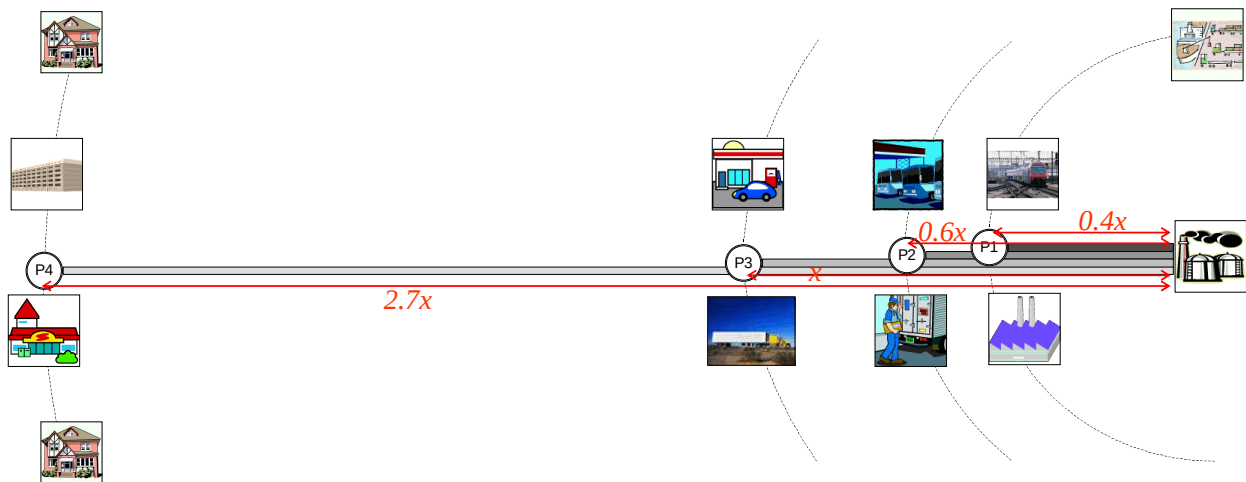
Local Distribution and Refueling (1)

- The model represents the **entire supply chain of final energy carriers**.
- The model considers the **capital and operating costs** of distribution and refueling separately by treating the corresponding **infrastructure**.
- These costs were estimated not only for each energy carrier, but also for each **end-use sector**, each **time point**, and each **region**.



Local Distribution and Refueling (2)

- Gaseous hydrogen demand points are classified into five groups depending on the degree of their distribution from a centralized hydrogen production plant.
- The five groups are:
 - (1) hydrogen-fired gas turbine power plants and international ocean shipping;
 - (2) industry, ordinary rail, and domestic shipping;
 - (3) fleet vehicles such as buses and medium-duty trucks;
 - (4) the other road vehicles (two-wheelers, light-duty vehicles, and heavy-duty trucks) ; and
 - (5) the residential/commercial sector.



Conceptual diagram of the distribution of gaseous hydrogen demand in a model region

Hydrogen End-Use Technologies

	Efficiency ratio to conventional ^a		Cost ratio to conventional ^b	
	2010	2100	2010	2100
H ₂ -fueled vehicles and boilers/furnaces				
FC hybrid (FCH) two-wheelers	2.56	2.76	5.26	1.35
FC hybrid (FCH) light-duty vehicles	2.56	2.76	2.54	1.23
FC hybrid (FCH) buses	1.59	1.72	3.78	1.15
FC hybrid (FCH) medium-duty trucks	1.69	1.74	4.34	1.11
FC heavy-duty trucks	1.36	1.39	3.64	1.11
FC hybrid (FCH) trains	1.67	1.71	4.61	1.12
FC hybrid (FCH) small ships	1.87	2.01	3.75	1.15
Liquid hydrogen subsonic aircraft	0.85	0.85	1.24	1.24
Boilers and furnaces	1.00	1.00	1.20	1.20

^a Conventional technology is assumed to be gasoline ICE for two-wheelers, light-duty vehicles, and medium-duty trucks, diesel ICE for buses, heavy-duty trucks, trains, and small ships, and natural gas boiler and furnace, respectively.

*The cost of PEMFC stacks for light-duty vehicles is assumed to drop to US\$₁₉₉₀60/kW.

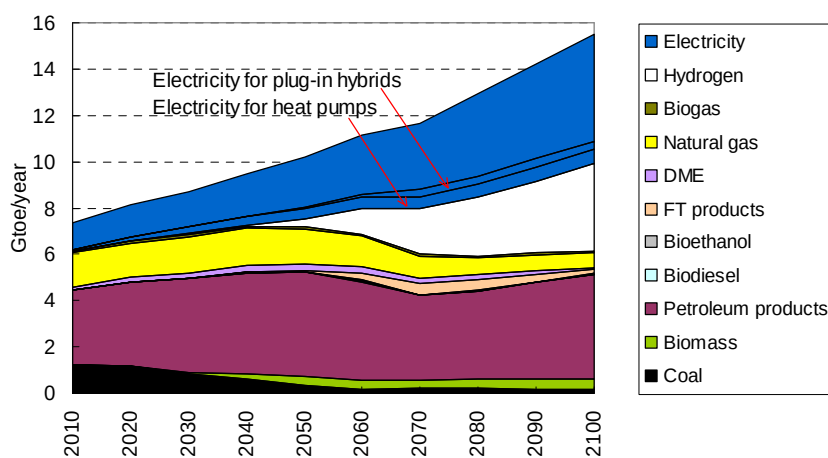
	Conversion efficiency (%, LHV basis)		Capital cost (US\$ ₁₉₉₀ /kW)	
	2010	2100	2010	2100
H ₂ -fueled stationary fuel cell power systems				
SOFCs for industrial use (100 kW-several MW)	52.5 (elec.) 32.6 (heat)	63.5 (elec.) 26.5 (heat)	4500	900
PEMFCs for residential/commercial use (1-200 kW)	50.0 (elec.) 33.9 (heat)	60.0 (elec.) 30.0 (heat)	5850	1170
SOFCs for residential/commercial use (1-200 kW)	45.5 (elec.) 39.6 (heat)	55.0 (elec.) 35.0 (heat)	5550	1110

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Competitiveness of Hydrogen

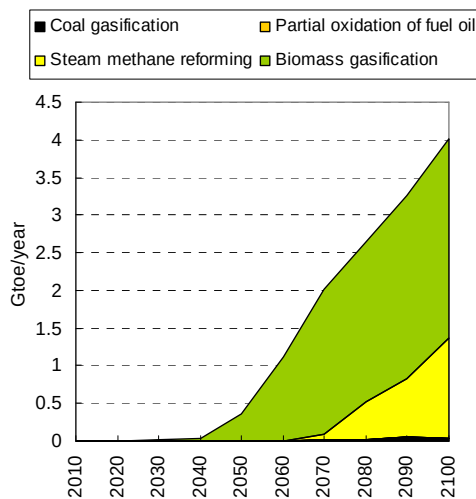
- Under the **stringent** climate stabilization constraint, **hydrogen** becomes **one of the important** final energy carriers in the **second half** of the century.
- **Electricity** plays a **major role** throughout the century and has the **largest** share in the global final energy mix from **2070 onward**.
- CO₂ mitigation technologies powered by **electricity** (i.e., **heat pumps** and **PHEVs**), which compete with hydrogen end-use technologies, are economically **highly attractive**.



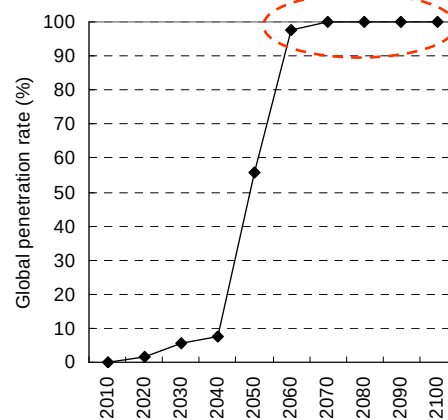
Global final energy consumption under the 400 ppmv CO₂ stabilization constraint

Cost-Effective Strategy for Producing H₂

- Although **biomass** is the main feedstock of choice for hydrogen production, the share of hydrogen produced from **steam methane reforming** in global hydrogen supply mix increases due to the **biomass resource constraint**.
- Hydrogen becomes one of the important final energy carriers under the CO₂ stabilization target of 400 ppmv **on the condition that CO₂ resulting from hydrogen production is properly captured and sequestered**.



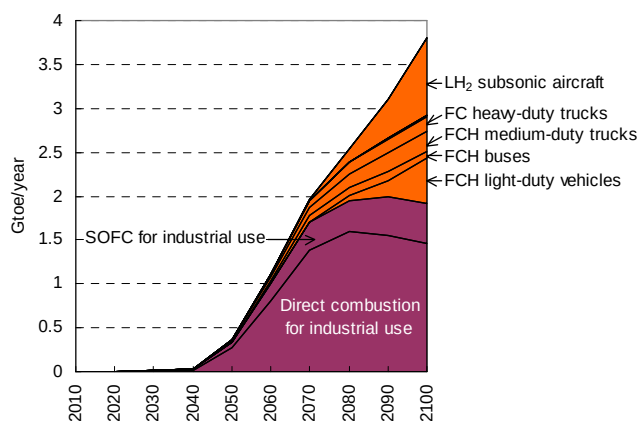
Global hydrogen supply mix under the 400 ppmv CO₂ stabilization constraint



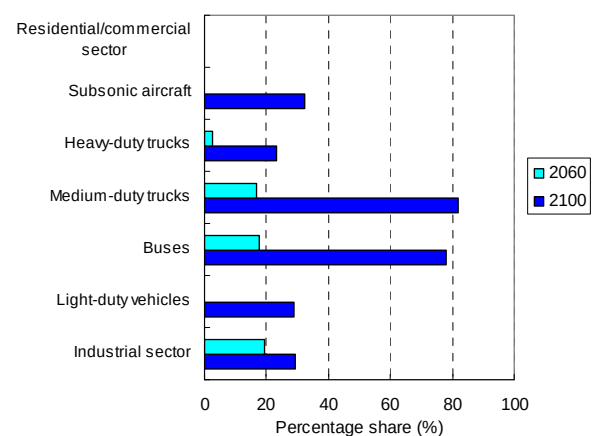
Global penetration rate of CO₂ capture in large-scale energy conversion plants

Cost-Effective Strategy for Using H₂

- The large scale use of hydrogen begins in the industrial sector, and hydrogen is not consumed in the residential/commercial sector.
- The sectoral difference in the requirement of a GH₂ distribution pipeline system has a significant impact on the competitiveness of hydrogen.
- Introducing cheap H₂-fired boilers/furnaces in the industrial sector would facilitate the replacement of natural gas with hydrogen.



Global final hydrogen consumption by sector under the 400 ppmv CO₂ stabilization constraint



Share of hydrogen in total energy use in the years 2060 and 2100 for each end-use sector

Summary: Major Findings

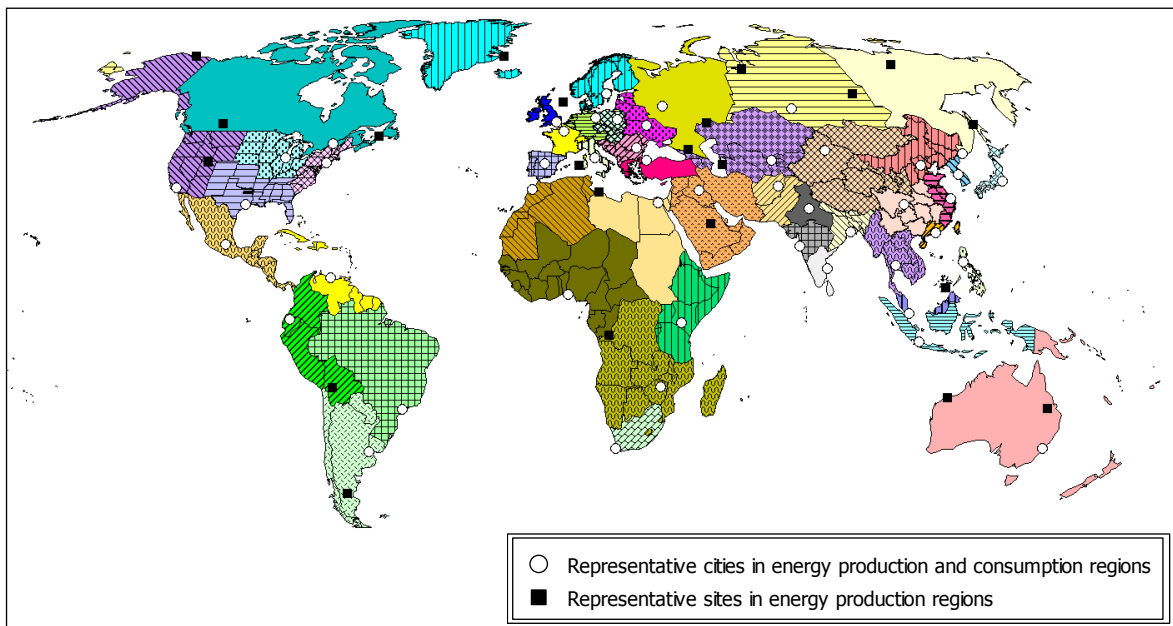
1. Under the 400 ppmv CO₂ stabilization constraint, hydrogen becomes one of the important final energy carriers in the second half of the century.
2. Hydrogen and electricity compete as substitute energy carriers in some end-use sectors (e.g., PHEV vs FCHV). For other uses, their differing properties give one or the other an advantage (e.g., H₂ preferred by aviation and electricity preferred by the res./comm. sector).
3. Hydrogen becomes one of the important final energy carriers under the CO₂ stabilization target of 400 ppmv on the condition that CO₂ resulting from hydrogen production is properly captured and sequestered.
4. The large scale use of hydrogen begins in the industrial sector, because the sectoral difference in the requirement of a GH₂ distribution pipeline system has a significant impact on the competitiveness of hydrogen.
5. Introducing cheap H₂-fired boilers/furnaces in the industrial sector would facilitate the replacement of natural gas with hydrogen.

Hydrogen Production Technologies

	Conversion efficiency (%, LHV basis)			Capital cost (US\$ ₁₉₉₀ /toe-fuel/year)		
	2000	2050	2100	2000	2050	2100
Offsite hydrogen production technologies						
Coal gasification	64.0	72.5	72.5	941	680	680
Partial oxidation of fuel oil	71.0	72.8	72.8	631	557	557
Steam methane reforming of natural gas	79.2	81.2	81.2	361	319	319
Biomass gasification (available from 2010)	(60.6)	68.7	68.7	(934)	675	675
Black liquor gasification (available from 2010)	(53.6)	60.8	60.8	(1319)	953	953
Water electrolysis using grid AC power	68.2	69.9	69.9	880	777	777
Water electrolysis using solar, wind, hydro, or nuclear DC power	71.0	72.8	72.8	676	597	597
I-S thermochemical water splitting cycle using nuclear heat (available from 2030)	(45.0)	51.0	51.0	(732)	585	585
I-S thermochemical water splitting cycle using solar heat (available from 2030)	(56.0)	63.4	63.4	(2684)	2143	2143
Onsite hydrogen production technologies						
Steam methane reforming of natural gas	72.8	74.6	74.6	1625	1434	1434
Water electrolysis using grid AC power	68.2	69.9	69.9	1977	1745	1745

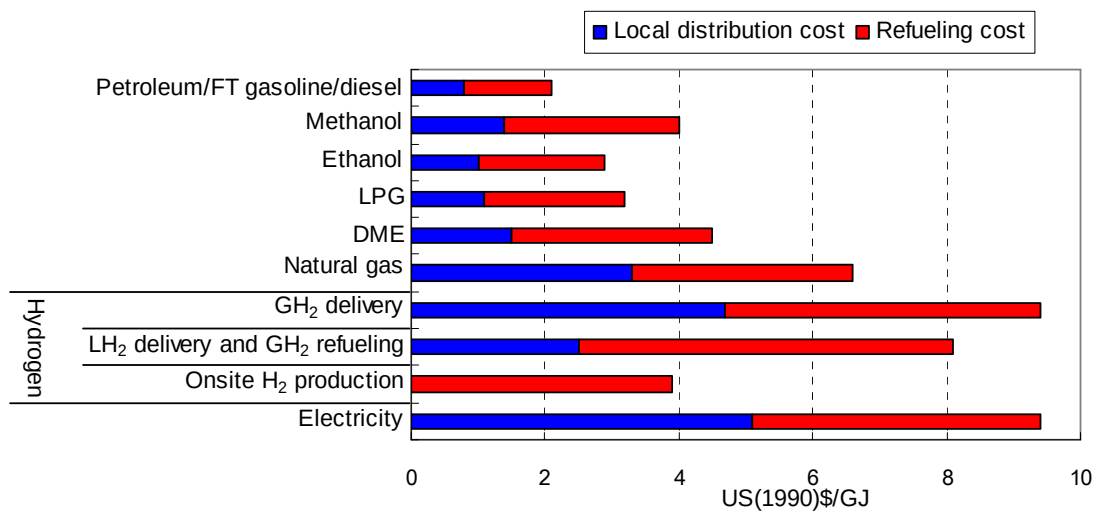
Regional Disaggregation of the Model

- Possible inter-regional energy transportation routes were given **between representative cities/sites** in the 70 model regions.
- For each possible route, the model determines **the need for transportation infrastructure construction** at each point in time.



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- Figure 1 is a line graph showing interregional transportation costs in US(1990)/\$toe versus distance (km). The x-axis ranges from 0 to 20,000 km, and the y-axis ranges from 0 to 250 US(1990)/\$toe. The graph displays various transportation modes and their costs over distance. The modes include Liquid H₂ tanker, Gaseous H₂ pipeline, Liquid H₂ rail, Biomass pellets freight rail, DME pipeline, Natural gas pipeline, LNG rail, Methanol pipeline, Coal freight rail, Ethanol pipeline, FT products pipeline, Biomass pellets freight ship, Oil pipeline, LNG tanker, Coal freight ship, DME tanker, Methanol tanker, Ethanol tanker, and FT products tanker. A red dashed box highlights the H₂-related modes.

Local Distribution and Refueling (3)

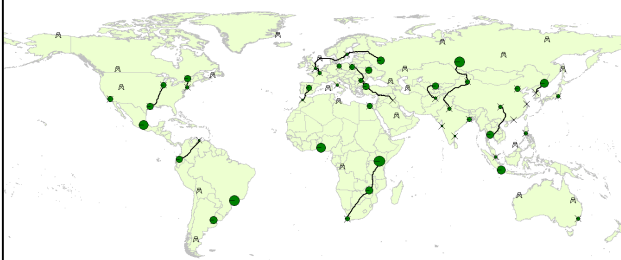


Local distribution and refueling costs associated with supplying light-duty vehicles

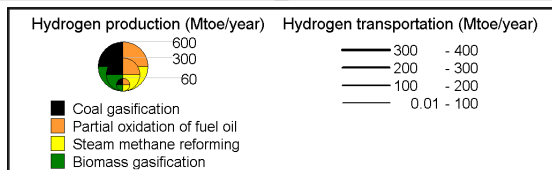
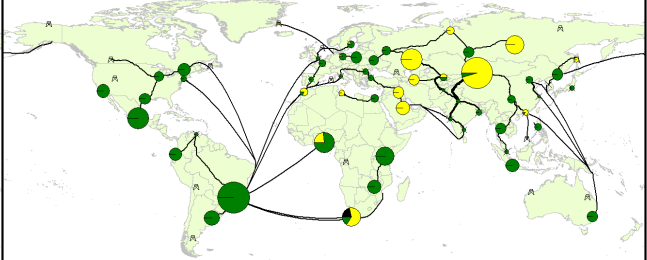
Cost-Effective Strategy for Transporting H₂

- H₂ production and consumption are **evenly distributed** around the world.
- **Pipeline transportation over short distances** is an important means of interregional hydrogen transportation.
- When the share of hydrogen increases further, natural gas becomes the main feedstock for hydrogen production, and **LH₂ aircraft** is selected, **hydrogen liquefaction** and **LH₂ tanker transportation** are done widely.

In 2060



In 2100

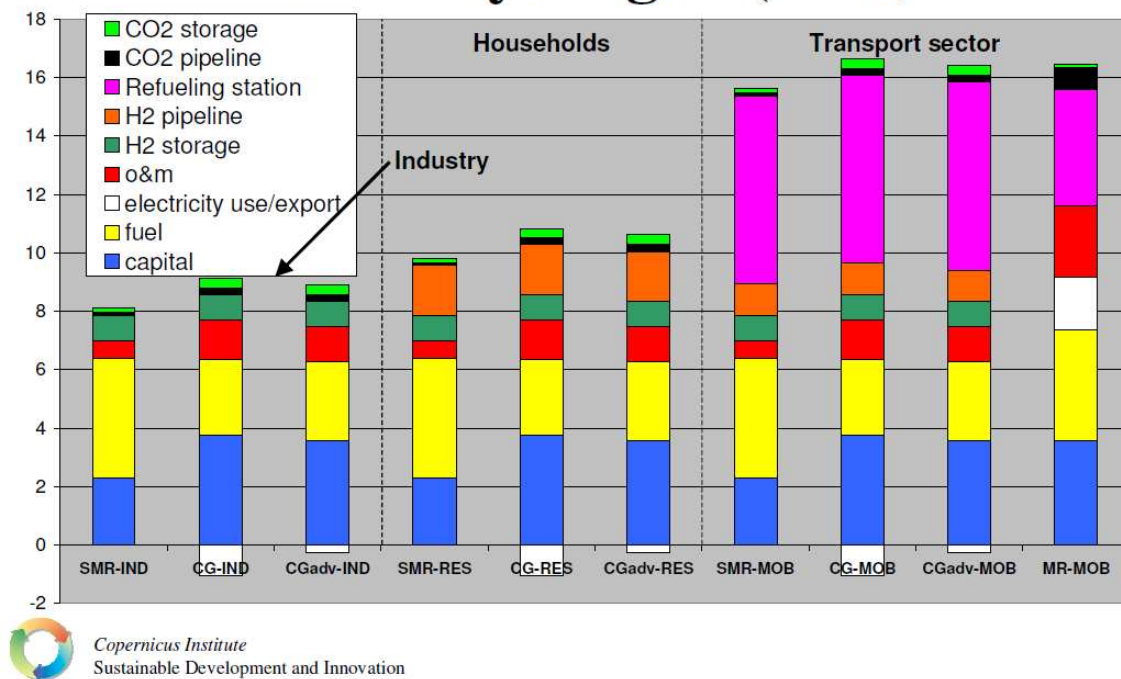


Hydrogen production and transportation under the 400 ppmv CO₂ stabilization constraint for the years 2060 and 2100



Universiteit Utrecht

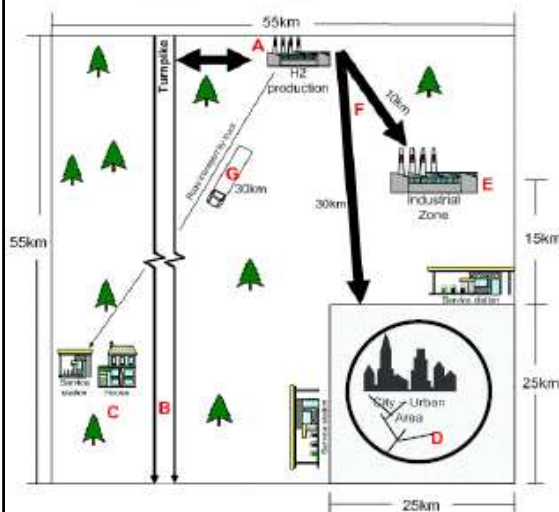
Cost of hydrogen (€/GJ)



Copernicus Institute
Sustainable Development and Innovation

Source: Damen et al. (2004)

Hydrogen distribution reference network



	2000							
	Turnpike	High pressure	Medium pressure	Low pressure	Service station connection €/GJ	Industry	Road transport	Total
Supply of Gaseous H ₂ at:								
Urban service stations	0.88	0.78	0.21		0.51			2.38
Urban households	0.88	0.78	0.21	4.68				6.55
Rural service stations	0.88						5.53	6.41
Rural households	0.88						5.53	6.41
Industry	0.88					0.07		0.95

Hydrogen distribution Costs

	Euro/GJ	
	2000	2050
Residential / Commercial	6.48	5.25
Industry	0.95	0.8
Cars	2.38	1.84

Source: Nam and Totschnig (2006)

Existing H₂-Fired Boilers



Source: DAISO CO., LTD. (2007)



Source: ASAHI GLASS (2008)

Table 4

Fuel	Power plants		Heat plants	
	Conversion efficiency (%)	Capital costs (USD/kW _e)	Conversion efficiency (%)	Capital costs (USD/kW _{Th})
Coal	50	1300	90	300
Oil	50	1000	90	100
Natural gas	60	700	90	100
Biomass	50	1300	90	300
Hydrogen	70	700	90	100
PV	n.a	1200		
Wind	n.a	600		
Hydropower	n.a	1000		

Sources: The estimates are based on various sources, including Gustavsson et al. (1995), ABB (1998), Neij (1999), IPCC (1996), and Larson and Marriison (1997). These estimates are intended to reflect the efficiency and the costs of the technologies once they are mature. Table 4

Source: Azar et al. (2003)

Aggregated world energy balance in 2000

		Coal	Biomass/ waste	Natural gas	Oil	Nuclear	Other renewable	Electricity	Heat	Total
		(EJ/yr)	(EJ/yr)	(EJ/yr)	(EJ/yr)	(EJ/yr)	(EJ/yr)	(EJ/yr)	(EJ/yr)	(EJ/yr)
Transformation Sector		-72.61	-4.17	-31.02	-12.91	-28.28	-11.27	55.25	11.77	-93.26
	Electricity/heat/CHP	-65.35	-2.40	-29.92	-12.45	-28.28	-11.27	55.27	11.75	-82.67
	Coke Ovens	-1.61	0.00	0.00	-0.05	0.00	0.00	0.00	0.00	-1.66
	Gas Works	-0.11	0.00	-0.08	-0.09	0.00	0.00	0.00	0.00	-0.28
	Blast Furnaces	-4.87	0.00	0.00	-0.05	0.00	0.00	0.00	0.00	-4.93
	Petroleum Refineries	0.00	-0.05	0.00	-1.21	0.00	0.00	0.00	0.00	-1.27
	Liquefaction Plants	-0.63	0.00	-0.99	0.95	0.00	0.00	0.00	0.00	-0.67
	Charcoal Production	0.00	-1.67	0.00	0.00	0.00	0.00	0.00	0.00	-1.67
	Non-specified /others	-0.06	-0.05	-0.02	0.00	0.00	0.00	0.00	0.00	-0.11
Energy Sector		-2.08	-0.01	-8.16	-8.70	0.00	0.00	-5.06	-1.06	-25.06
	Oil and Gas Extraction	0.00	0.00	-5.69	-0.60	0.00	0.00	-0.49	-0.18	-6.96
	Coke Ovens	-0.72	0.00	-0.02	0.00	0.00	0.00	-0.01	-0.01	-0.77
	Blast Furnaces	-0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.10
	BCB Plants	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01
	Petroleum Refineries	-0.01	0.00	-1.55	-7.82	0.00	0.00	-0.64	-0.59	-10.62
	LNG Plants	0.00	0.00	-0.64	0.00	0.00	0.00	0.00	0.00	-0.65
	Own Use Elec/heat	-0.56	0.00	-0.04	-0.10	0.00	0.00	-3.17	-0.09	-3.97
	Non-specified /others	-0.68	0.00	-0.19	-0.06	0.00	0.00	-0.55	-0.09	-1.57
Final Consumption		22.10	41.27	47.76	124.46	0.00	0.27	45.40	9.93	291.19
	Industry Sector	6.53	6.73	22.04	24.86	0.00	0.02	19.10	3.98	93.27
	Iron and Steel	5.54	0.20	2.16	0.73	0.00	0.00	2.24	0.40	11.28
	Chemical	1.99	0.20	8.95	14.30	0.00	0.00	3.04	1.29	29.77
	Non-Ferrous Metals	0.47	0.00	0.84	0.42	0.00	0.00	1.96	0.26	3.95
	Non-Metallic Minerals	3.76	0.15	1.67	1.50	0.00	0.00	1.01	0.12	8.21
	Transport Equipment	0.14	0.00	0.40	0.19	0.00	0.00	0.59	0.04	1.36
	Machinery	0.37	0.00	0.99	0.42	0.00	0.00	1.67	0.45	3.90
	Mining and Quarrying	0.16	0.00	0.19	0.46	0.00	0.00	0.64	0.02	1.47
	Food and Tobacco	0.66	0.86	1.35	0.81	0.00	0.00	1.09	0.35	5.12
	Paper, Pulp and Print	0.56	2.10	1.23	0.65	0.00	0.01	1.61	0.12	6.27
	Wood/ Wood Products	0.06	0.45	0.12	0.15	0.00	0.00	0.32	0.28	1.38
	Construction	0.16	0.00	0.11	0.61	0.00	0.00	0.17	0.07	1.13
	Textile and Leather	0.34	0.01	0.39	0.56	0.00	0.00	0.69	0.15	2.14
	Non-specified	2.31	2.76	3.63	4.06	0.00	0.01	4.09	0.44	17.29
	Transport Sector	0.25	0.35	2.25	71.23	0.00	0.00	0.80	0.00	74.87
	International Air	0.00	0.00	0.00	4.97	0.00	0.00	0.00	0.00	4.97
	Domestic Air	0.00	0.00	0.00	4.38	0.00	0.00	0.00	0.00	4.38
	Road	0.00	0.35	0.12	58.91	0.00	0.00	0.00	0.00	59.38
	Rail	0.24	0.00	0.00	1.37	0.00	0.00	0.59	0.00	2.20
	Pipeline Transport	0.00	0.00	2.12	0.00	0.00	0.00	0.11	0.00	2.23
	Internal Navigation	0.00	0.00	0.00	1.43	0.00	0.00	0.00	0.00	1.43
	Non-specified	0.00	0.00	0.01	0.17	0.00	0.00	0.09	0.00	0.27
	Agriculture	0.51	0.25	0.27	4.27	0.00	0.00	1.27	0.23	6.80

Source: IEA (2004)

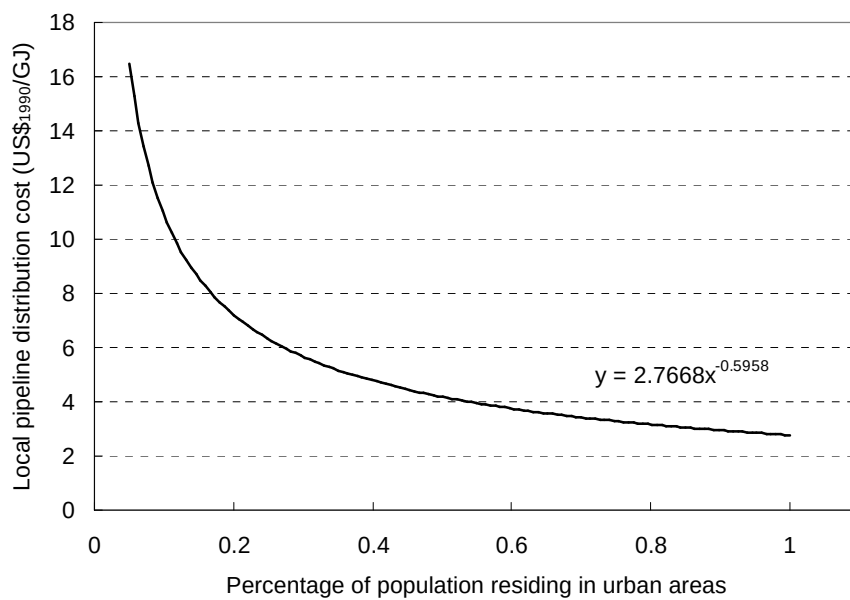
Possibility of Fuel Switching to H₂

- The **structure of energy use** in each industrial sector has been examined to derive the **possibility of fuel switching to hydrogen**.
- According to IEA (2005), hydrogen can be used by **all types of burners where natural gas is used**, provided that proper adjustments are made. IEA (2005) also states that hydrogen could be used for steam generation in **natural gas-fired boilers** or combined heat and power units.

	Boilers	Direct heating	CHP	Feedstocks	Others
Coal	10118.108	13525.226	0	27928.043	51.623
Coke	0	26110.14	0	399.645	133.215
Petroleum coke	1582.335	1347.915	0	968.936	3.907
Crude oil	14.66	0	0	1451.34	0
Oil gas	1604.85	7411.924	746.34	3328.352	1135.06
Naphtha	0	26.033	0	26006.967	0
Gasoline	0	0	0	0	125
Kerosene	706.112	918.544	353.056	359.04	658.24
Light oil	5344.464	1505.488	1629.6	1.092	1593.42
Fuel oil	10095.066	2684.025	806.49	55.62	375.894
Oil produced by conversion	0	0	0	1108	0
Hydrocarbon oil	1335.312	477.576	38.016	496.584	28.512
Natural gas	382.542	991.163	159.293	186.887	122.115
Town gas	2006.8	2214.4	1923.76	0	781.96
Exhaust gas in the iron and steel industry	3662.773	8454.741	468.27	12.144	426.243
Black liquor	4347	0	0	0	0
Waste tires	45.872	141.94	0	0	0
(%)	22.8	36.4	3.4	34.4	3.0

Source: METI (2008)

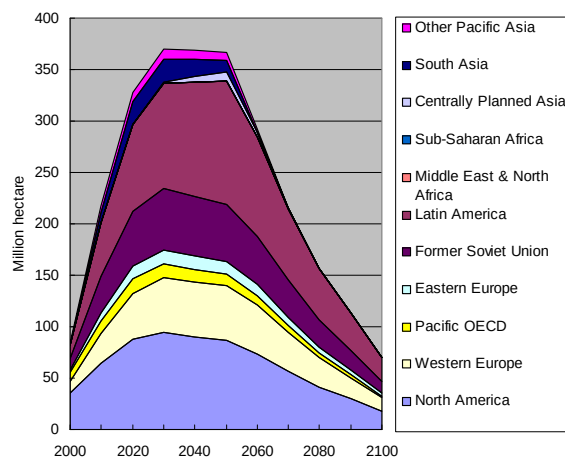
Cost of Local Pipeline Delivery of H₂



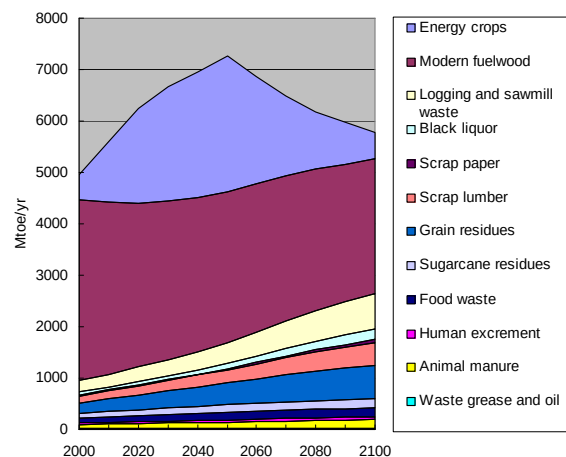
Cost of local pipeline delivery of hydrogen to refueling stations for light-duty vehicles

Global Supply Potential of Bioenergy

- The availability of various biomass feedstocks and excess cropland that can be used for energy purposes **without conflicting with other biomass uses such as food production** were estimated for each of the 11 world regions and each time period based on Yamamoto et al. (2001), Fischer and Schrattenholzer (2001), and IEA (2004).
- These estimates were made under the assumption that **biomass should be produced in a sustainable way** so that biomass-derived energy carriers can be regarded as carbon neutral.



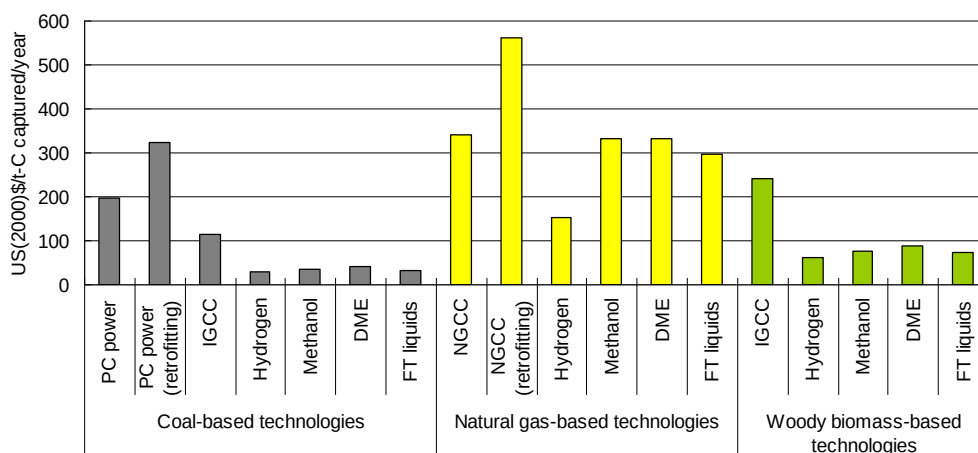
Global amount of the excess cropland that can be used for energy purposes



Global supply potential of bioenergy by type of feedstock

CO₂ Capture: Assumptions and Costs

- The cost of a CO₂ capture system scales with the amount of CO₂ captured, which has a scaling factor of 0.608.
- For typical modern energy conversion plants, the assumed feed rate is 1632 MW_{in} for coal, 704 MW_{in} for natural gas, and 344 MW_{in} for biomass.
- Comparing the incremental costs of CO₂ capture by feedstock, the diseconomies of small scale in biomass-based plants are completely offset by the high carbon content of biomass and their low efficiency.



Estimated incremental capital costs of CO₂ capture