Well-to-Wheel Efficiency Analysis

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Chairman, Total Efficiency Study Group

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Purpose of Analysis

Efficiency

Summarize well-to-wheel (WtW) efficiency data of various highly energy-efficient low-emission vehicles (alternative fuel vehicles), mainly fuel cell vehicles (FCVs), with regard to Japan-specific conditions, and to

Compile collected data into quantitative figures, objective enough to be dealt with as official ones.

- Main Focus

  WtW energy efficiency, and
  WtW CO2 emissions

Past Activities

Efficiency

JEVA Total Efficiency Research Group was established within the former *Japan Electric Vehicle Association* (*JEVA*) to analyze WtW energy efficiency of clean energy vehicles

- Period: FY 1999 ~ 2002
- Members: Automakers, Oil companies
- Group Mission:
  - Main task: Tank-to-Wheel energy efficiency analysis
  - Data were provided by participating automakers
  - Main activities:
    - Collection of basic data on WtW efficiency
    - Evaluation of energy efficiency of gasoline ICEs, diesel ICEs, CNG vehicles, and BEVs
    - Evaluation of efficiency of fuel cell components
    - Evaluation of energy efficiency of FCVs
    - Presentation of the results at EVS-18 and EVS-20

Concepts of Data Collection

Efficiency

FY 1999 - 2002 (conducted by JEVA)

- **Main focus: energy efficiency of vehicles (tank-to-wheel efficiency)**
- **The published data were adopted for Well-to-Tank energy efficiency data**

FY 2003 - 2005 (conducted by the Study Group)

- **Main focus: energy efficiency of fuel infrastructure (well-to-tank efficiency)**
- **Published data and demonstration data at each JHFC station are evaluated**
- ***By applying previous results by JEVA's tank-to-wheel analysis, total Well-to-Wheel efficiency are evaluated***

Concept of Data Collection

- **Collect and Evaluate openly published data, and arrange as the database input**
- **Review current energy status in Japan (energy paths, automotive technologies)**
- **Compile data to reflect current state of arts and future estimate(10 years ahead)**
- **Apply expected / targeted data for emerging technologies**

[Note] Japanese and European driving modes are used to calculate WtW efficiency, and to identify characteristics of the modes.

Organizational Structure

Efficiency

[Organization]

Total Efficiency Study Group
Chairman: Prof. Ishitani

Total Efficiency WG
Chief: Prof. Ishitani

[Members]

- JHFC Steering Committee members
- Other stakeholders in FC-related businesses / institutions / associations and academic area(universities and institutes)

Collect relevant data through various stakeholders

Members

Efficiency

Non-JHFC members are underlined

[Universities / Research institutes]

Keio Univ., Tokyo Institute of Technology, Univ. of Tokyo, Yokohama National Univ., Tsukuba Univ., National Institute for Environmental Studies, National Institute of Advanced Industrial Science and Technology (AIST), Institute of Energy Economics, Japan (IEEJ)

[Associations]

Japan Automobile Manufacturers Association (JAMA), Japan Gas Association, Fuel Cell Commercialization Promotion Conference (FCCJ), Petroleum Association of Japan, Federation of Electric Power Companies, WBCSD Fuel Work Stream

[Companies]

Toyota Motor Corp.
Nissan Motor Co., Ltd.
Honda Motor Co., Ltd.
General Motors Corp. (GM)
DaimlerChrysler AG
Mitsubishi Motors Corp.
Suzuki Motor Corp.

Nippon Oil Corp. Cosmo Oil Co., Ltd.
Show Shell Sekiyu K.K.
Tokyo Gas Co., Ltd.
Iwatani International Corp.
Taiyo Nippon Sanso Corp.
Japan Air Gases Ltd.

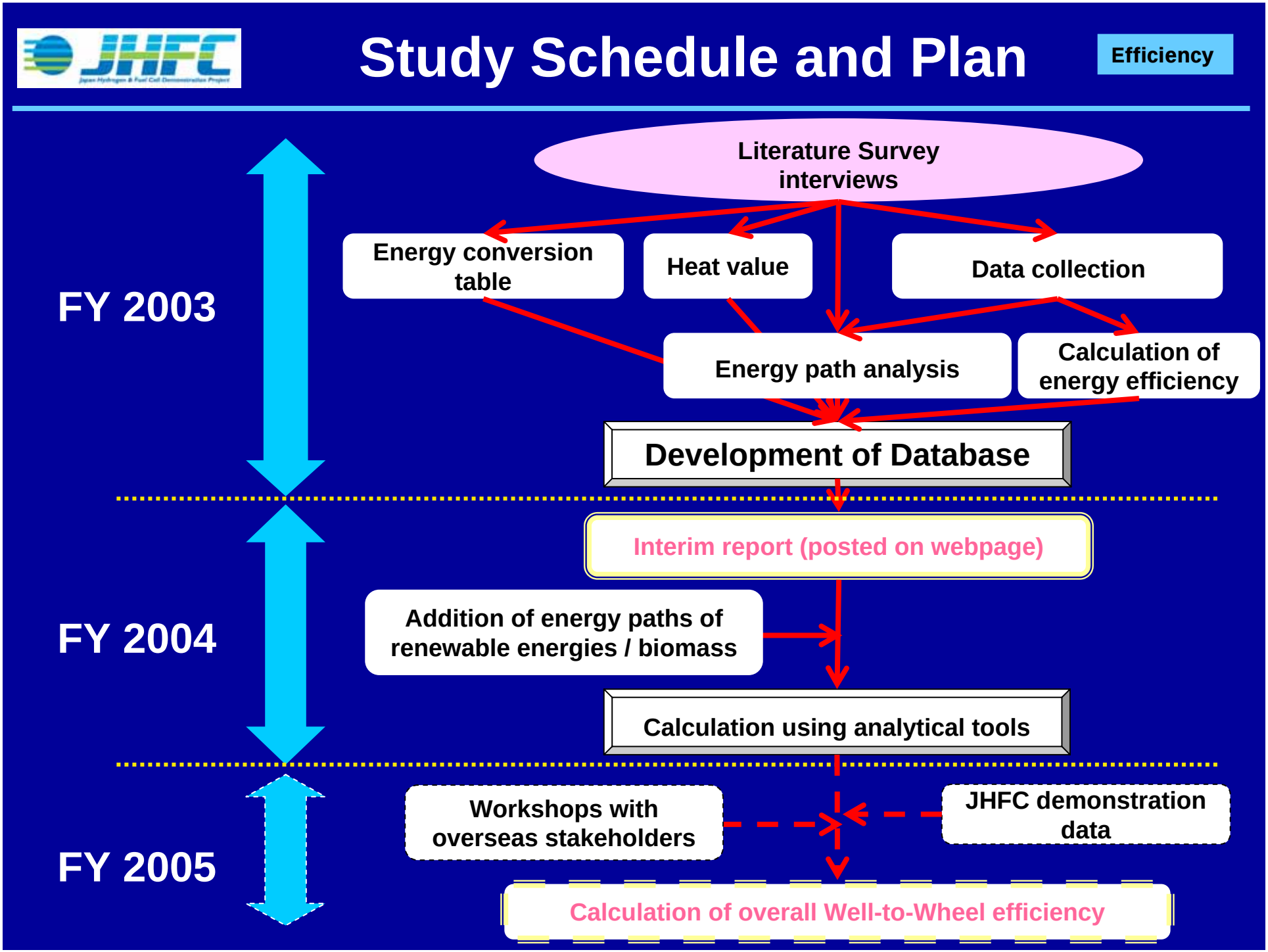
Nippon Steel Corp.
Idemitsu Kosan Co., Ltd.
Kurita Water Industries Ltd.
Itochu Enex, Co., Ltd.
Babcock Hitachi
Sinanen Co., Ltd.
Toho Gas Co., Ltd.

Total: 35 members

[Observers] Ministry of Economy, Trade and Industry, NEDO, PEC
[Secretariat] ENAA, JARI and consultancy

Study Schedule and Plan

Efficiency



Overall Efficiency Analysis: Work Roles

Efficiency

Framework of Analysis by Total Efficiency Study Group

Review of published / demonstrated data (FY 2003 ~)

Data reviewed by JEVA study (~ FY 2002)

Demonstrated data are used if they are to be in public domain

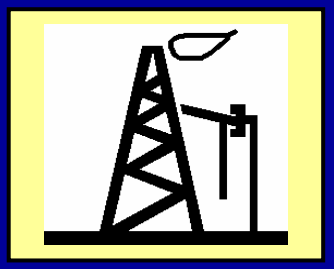
Analysis of demonstration data

Data Evaluation WG

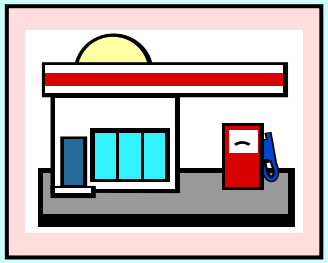
Hydrogen Station Data WG

Automotive Data WG

Well

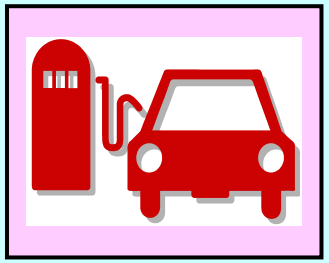


Charge Tank



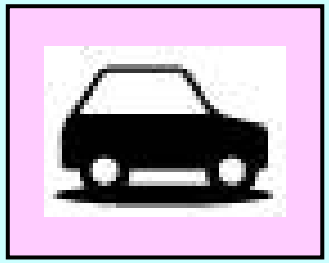
Fuel tank at station

Fuel Tank



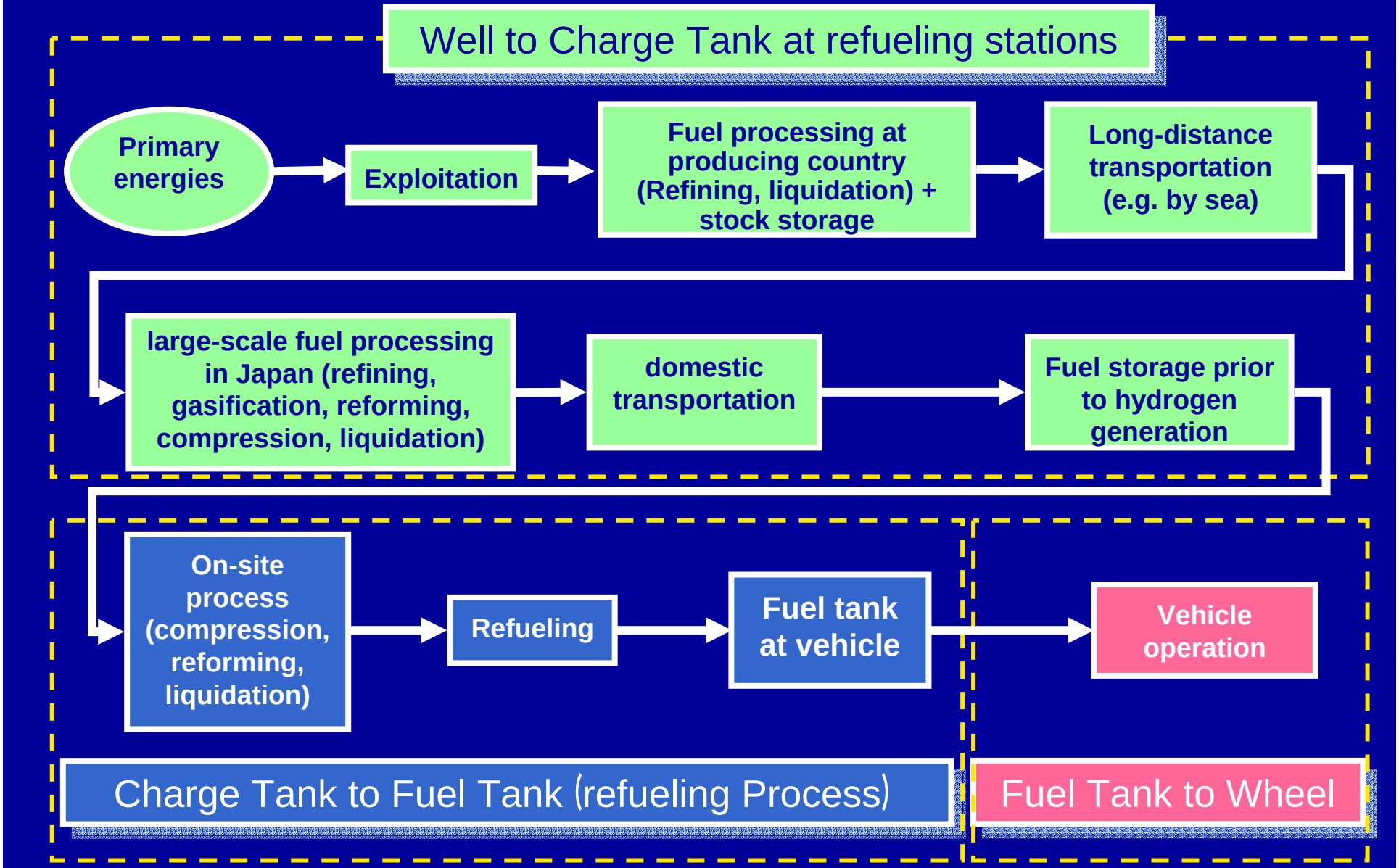
Fuel tank at vehicle

Wheel



Concept of Energy Path

Efficiency



Status of Data Collection

Interview and Published Data Analysis

Efficiency

【Interview】

	Interviewee	Data Collected
FY 2003	Nippon Oil Corp.	•Information on heat value / energy efficiency of by-product hydrogen at steel plants
	LP Gas Association	•Information on LPG industry •Information on heat value of LPG
	Petroleum Association of Japan	•Information on heat value / energy efficiency of GTL
	Tsurumi Soda Co., Ltd.	•Information on caustic soda industry •Information on heat value / energy efficiency of caustic soda process
	Federation of Electric Power Companies	•Information on energy efficiency of power generation (by fuel type), transmission, and distribution
	Japan Gas Association	•Information on city gas industry •Information on heat value / energy efficiency of NG
	Institute of Energy Economics, Japan	•Data on efficiency of LPG
FY 2004	JOGMEC (Former JNOC)	•Information on GTL, and other related issues
	Shell (Netherlands)	•Information on GTL
	JGC Corp.	•Information on FT diesel, naphtha, LPG
	GM (LBST)	•Information exchange on Well-to-Wheel efficiency analysis

【Published Data Analysis】

- Domestic data from: WE-NET, PEC, and others — 43 papers
- Overseas data from: LBST (GM), and others — 15 papers

Result I : Energy Conversion Table

Efficiency

	MJ	kcal (International table)	kcal (Measurement Law)	BTU	kl oe	t oe	kWh
MJ	1	238.846	238.889	947.817	2.58258 E-05	2.38846 E-05	0.277778
kcal (International table) *1	4.18680 E-03	1	1.00018	3.96832	1.08127 E-07	1.00000 E-07	1.16300 E-03
kcal (Japan's Measurement Law) *2	4.18605 E-03	0.999821	1	3.96761	1.08108 E-07	9.99821 E-08	1.16279 E-03
BTU	1.05506 E-03	0.251996	0.252041	1	2.72477 E-08	2.51996 E-08	2.93071 E-04
kl oe (kiloliters of oil equivalent)	3.87210 E+04	9.24834 E+06	9.25000 E+06	3.67004 E+07	1	0.924834	1.07558 E+04
t oe (tons of oil equivalent)	4.18680 E+04	1.00000 E+07	1.00018 E+07	3.96832 E+07	1.08127	1	1.16300 E+04
kWh	3.60000	859.845	859.999	3.41214 E+03	9.29729 E-05	8.59845 E-05	1

*1 International table calorie: 4.18680×10^{-3}(MJ/kcal)

*2 Measurement law calorie: 4.18605×10^{-3}(MJ/kcal)

Definition	Basic conversion rate	Derived conversion rate

Result II: Heat Value Table

Efficiency

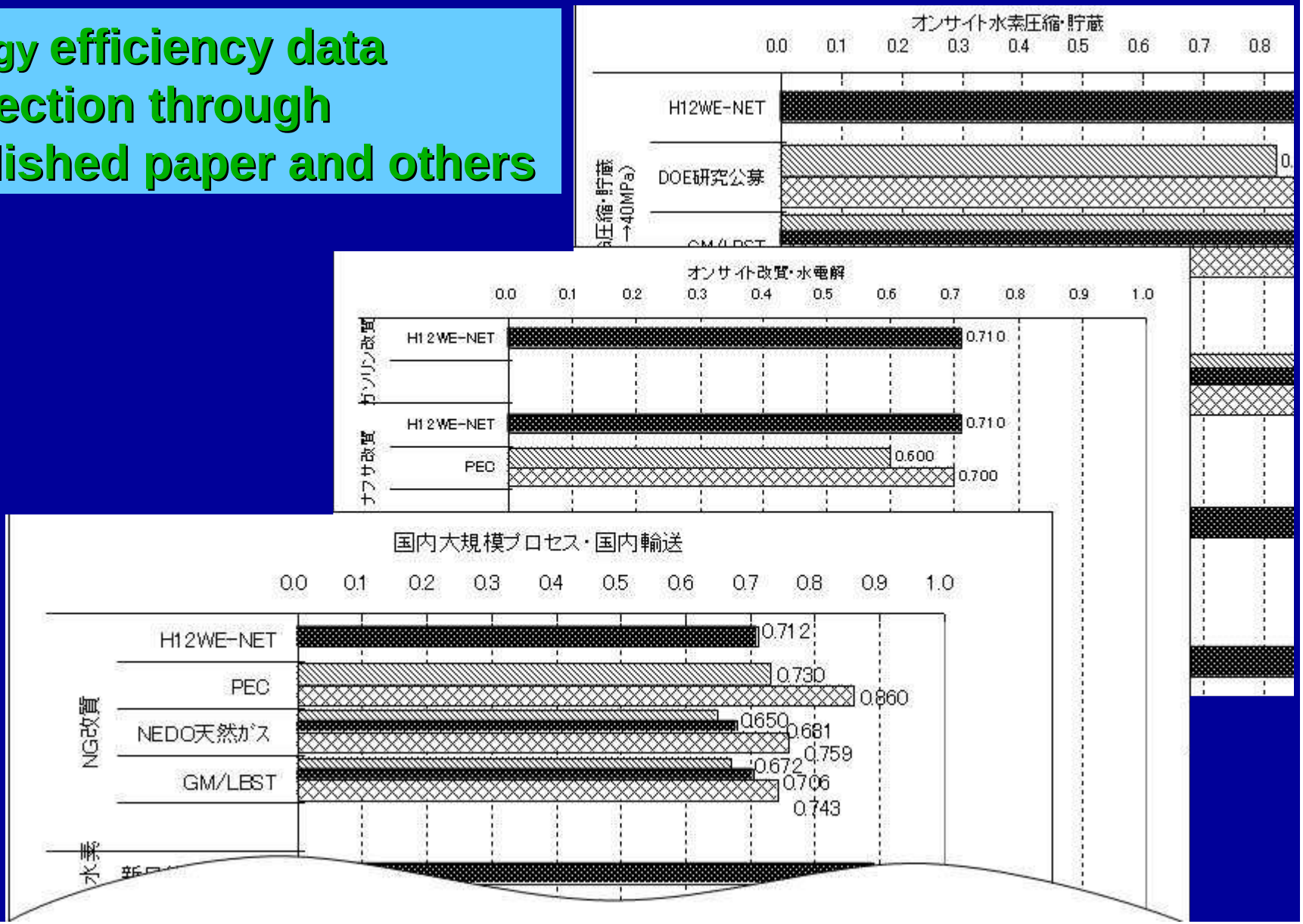
Unit equivalent	kg/ m^3(nor), kg/l	LHV,HHV
Heat value	MJ/kg,MJ/m^3(nor), MJ/l, MJ/kWh	LHV,HHV
	MJ/kg equivalent	LHV,HHV
CO_2 emission coefficient	CO_2-g/MJ CO_2-kg/kg,CO_2-kg/kWh	LHV,HHV

	Unit	Unit conversion constant	Heat Value			Heat Value in MJ/kg		
			Unit	LHV	HHV	Unit	LHV	HHV
Coal								
Coking coal (Imported)	—	—	MJ/kg	28.2	28.9	MJ/kg	28.2	28.9
Steam coal (Imported)	—	—	MJ/kg	25.9	26.6	MJ/kg	25.9	26.6
Coke	—	—	MJ/kg	30.1	30.1	MJ/kg	30.1	30.1
Byproduct gas fr. ironmaking								
Coke oven gas	kg/Nm3	0.470	MJ/Nm3	18.7	21.1	MJ/kg	39.8	44.9
Blast furnace gas	kg/Nm3	1.365	MJ/Nm3	3.35	3.41	MJ/kg	2.45	2.50
Converter gas			MJ/Nm3	8.38				
Petroleum								

Result III : Efficiency Data

Efficiency

Energy efficiency data Collection through published paper and others



Concepts of WtW Efficiency / CO_2 Emissions Analysis

Criteria for Reviewing Energy Path

Efficiency

- **Type of Vehicles (FCVs)**

  Passenger cars (excl. trucks and buses)

- **Vehicles for comparison**

  Gasoline ICEs, Diesel ICEs, Hybrid cars, CNGVs, Battery EVs

- **Fuels (hydrogen sources)**

  Crude oil, Natural gas (city gas), LPG, GTL, DME,
  By-product gas, Hydrogen from renewable energies , Biomass

- **Type of FCV system**

  Pure hydrogen, HC fuel with on board reformer

- **Hydrogen** Storage

  Compressed hydrogen, liquid hydrogen

- **Target year for calculation**

  Today, future (around 2010)

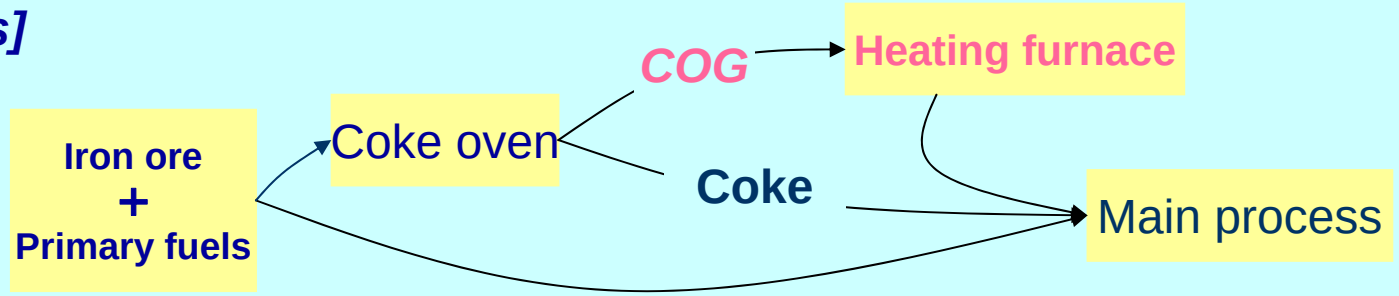
Calculation Methodology for By-product Hydrogen

Efficiency

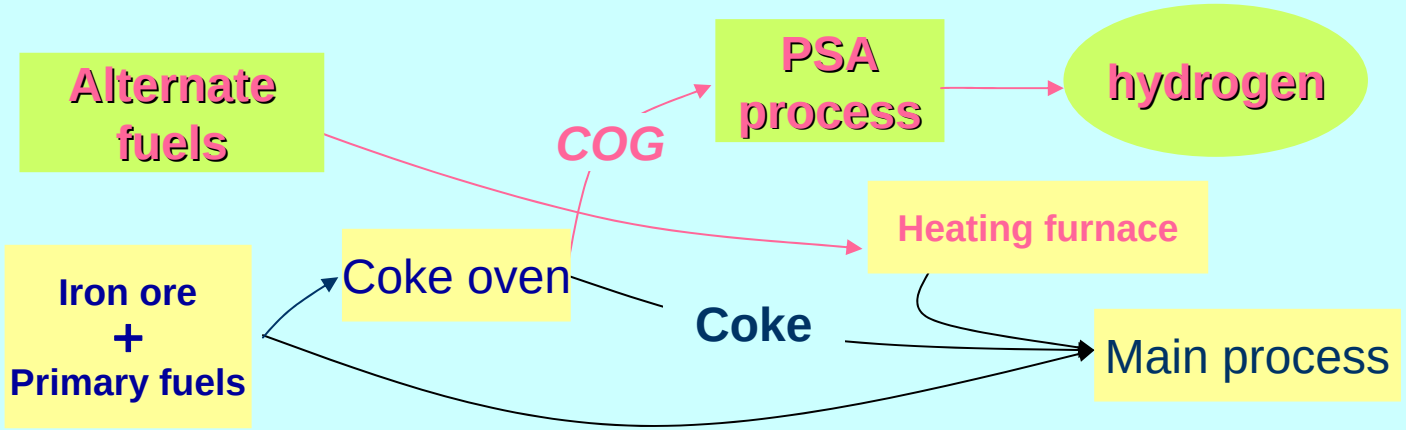
- Currently iron industry and caustic soda industry use Coke oven gas / by-product hydrogen as fuel for processing (e.g. heating furnaces) within a pant .
- If such hydrogen is used for FCVs, alternate fuels are needed for such processes.

[Coke oven gas]

Currently COG is used for heating furnace fuel



If COG is used for hydrogen production for FCVs, alternate fuels are needed for iron process

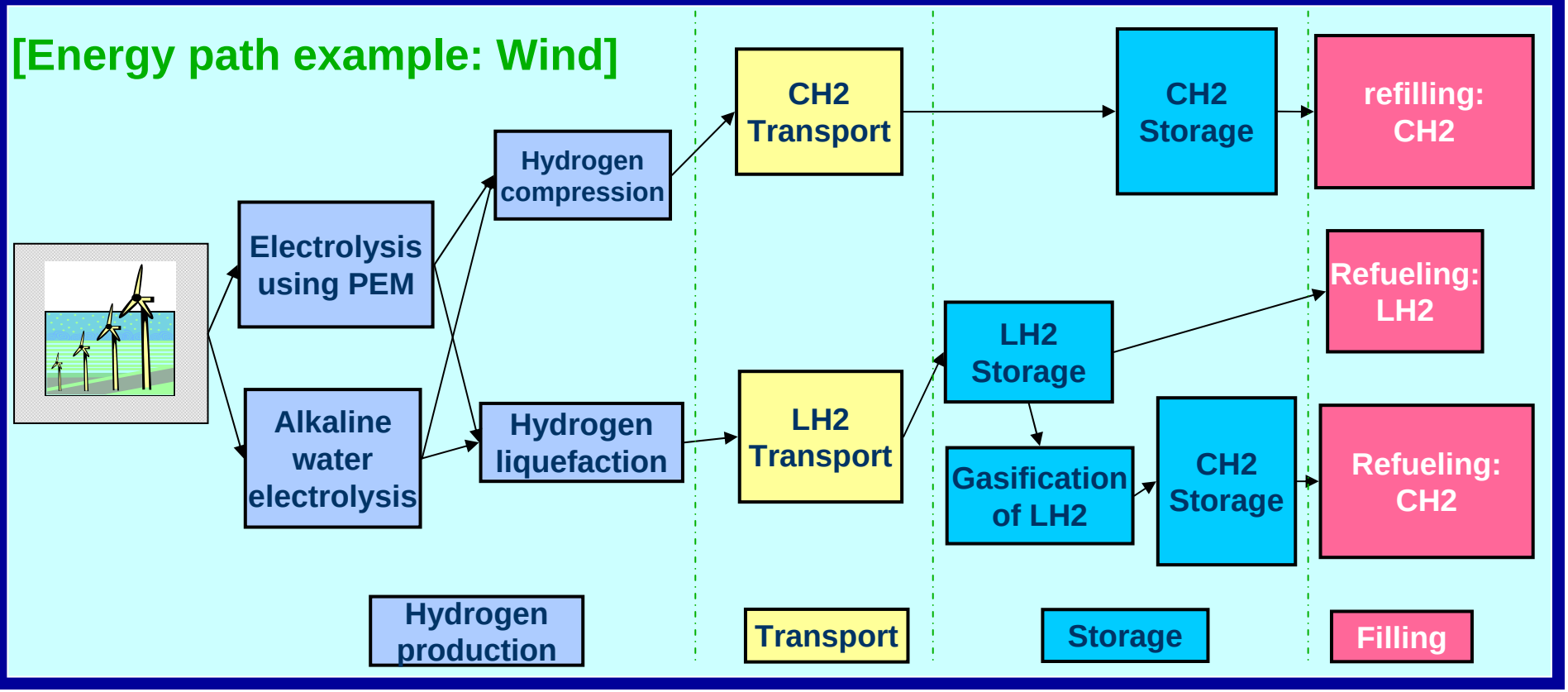


Energy and CO2 is calculated by using the difference between "using hydrogen" and "current status."

Calculation Methodology for Renewable Energies

Efficiency

[Energy paths Analyzed]
- Renewable Energies: solar (PV) , and wind power
- No grid connection
- Solar: On-site production
- Wind: Off-site production, trucking to stations



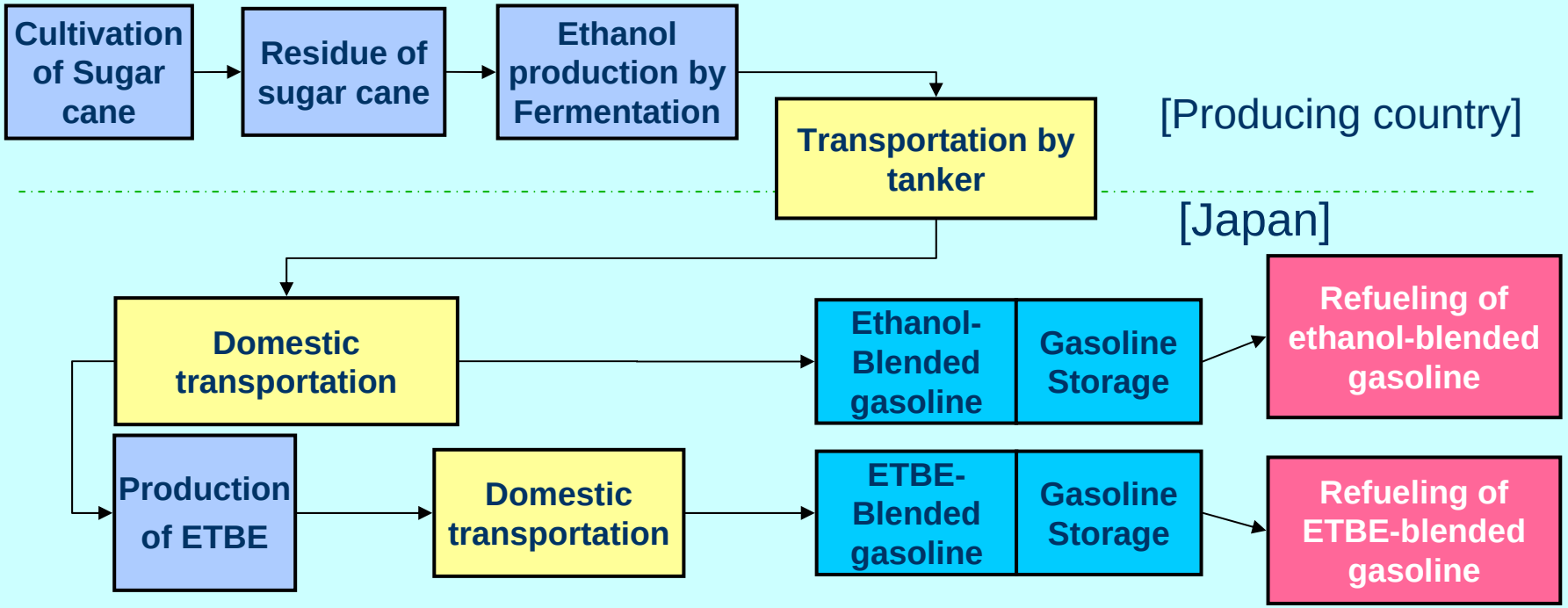
Calculation Methodology for Biomass Fuel

Efficiency

[Energy paths Analyzed] (paths which may become reality in Japan)

- Bio-diesel from waste cooking oil
- Ethanol from sugar cane (imported from Brazil and others)
- Ethanol from waste lumber (Japan)
- Methane from sewage sludge / livestock manure

[Energy path example: Ethanol from Sugar Cane]



Sensitivity Analysis For Efficiency Calculation

Efficiency

Definition at the study:

Sensitivity analysis means **the analysis of degree of influence on overall efficiency results, caused by variations / errors / uncertainties of composing efficiency data.**

Sensitivity analysis is conducted, if
- there is uncertainty of prospects on technology development
- there is inconsistency, or large variations among published data

Preconditions:

Changes in non-technological aspects are not considered
(e.g. change of fuel/energy-exporting countries)

Items subject for sensitivity analysis:

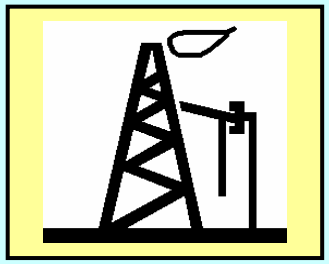
- **Domestic large-scale reforming process (naphtha, natural gas)**
- **On-site reforming (all fuels)**
- **Hydrogen compression storage**
- **EV charging system**

Results of WtW Efficiency / CO_2 Emissions Analysis

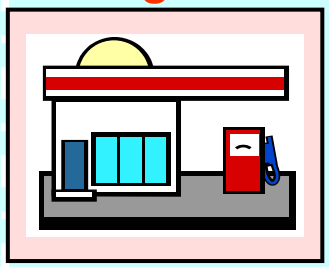
Outline of Used Data

Efficiency

W：Well

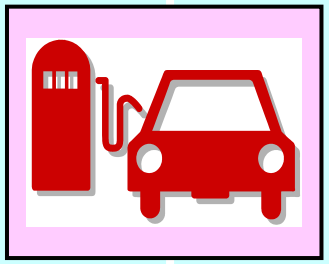


Charge Tank



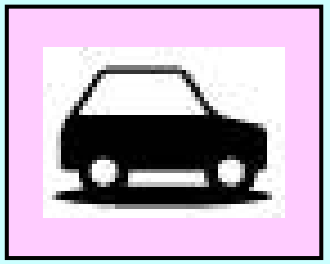
Fuel tank at station

Fuel Tank



Fuel tank at vehicle

Wheel



Well to Charge Tank

Charge Tank to Fuel Tank

Fuel Tank to Wheel

JHFC Demonstration Data

・JHFC Demonstrated Data
・Estimate data when commercialized

・10・15 Mode Test Data (Average + Top Runner)

Published Data

Published Data

Estimates based on "the former JEVA's Activities " and "JHFC demonstration data for FCV"

Definition of Calculated Data

Efficiency

"Primary energy input (MJ/km)" and "total CO2 emission (g-co2/km)"per 1km vehicle driving are calculated, back to primary energy.

Efficiency

①Well to Fuel Tank ：Primary fuel input unit (per unit vehicle energy) $= \frac{\text{Primary energy input (MJ)}}{\text{Fuel final energy (MJ)*}} = a$

② Fuel Tank to Wheel ： Fuel consumption energy per 1km driving*(MJ/km) $= b$

Well to Wheel ： Primary energy input per 1km driving (MJ/km) $= a \times b$

CO2

① Well to Fuel Tank ： $\frac{\text{CO2 emission(g-CO2)}}{\text{Fuel energy (MJ)*}} = c$

② Fuel Tank to Wheel ： CO2 emission per 1km driving (g-CO2/km) $= d$

Well to Wheel ：Total CO2 emission per 1km driving (g-CO2/km) $= b \times c + d$

*This calculation uses 120MJ/kg (air pressure at 25℃) as vehicle hydrogen energy for convenience.

Efficiency / CO_2 Emissions Analysis

“Well to Fuel Tank”

"Well to Fuel Tank" Calculation Criteria

Efficiency

- Fuels (hydrogen source)

  Crude oil, Natural gas (city gas), LPG, GTL, DME, by-product gas, hydrogen from renewable energies, biomass

- Hydrogen

  Compressed hydrogen, liquid hydrogen

- Vehicle fuel for comparison

  Gasoline, diesel, CNG, electric

- Electric sources

  - Average electric power generation mixed in Japan

  - Electricity from the same fuel origin (ex: natural gas electric power generation at from natural gas path)

- Target year for calculation

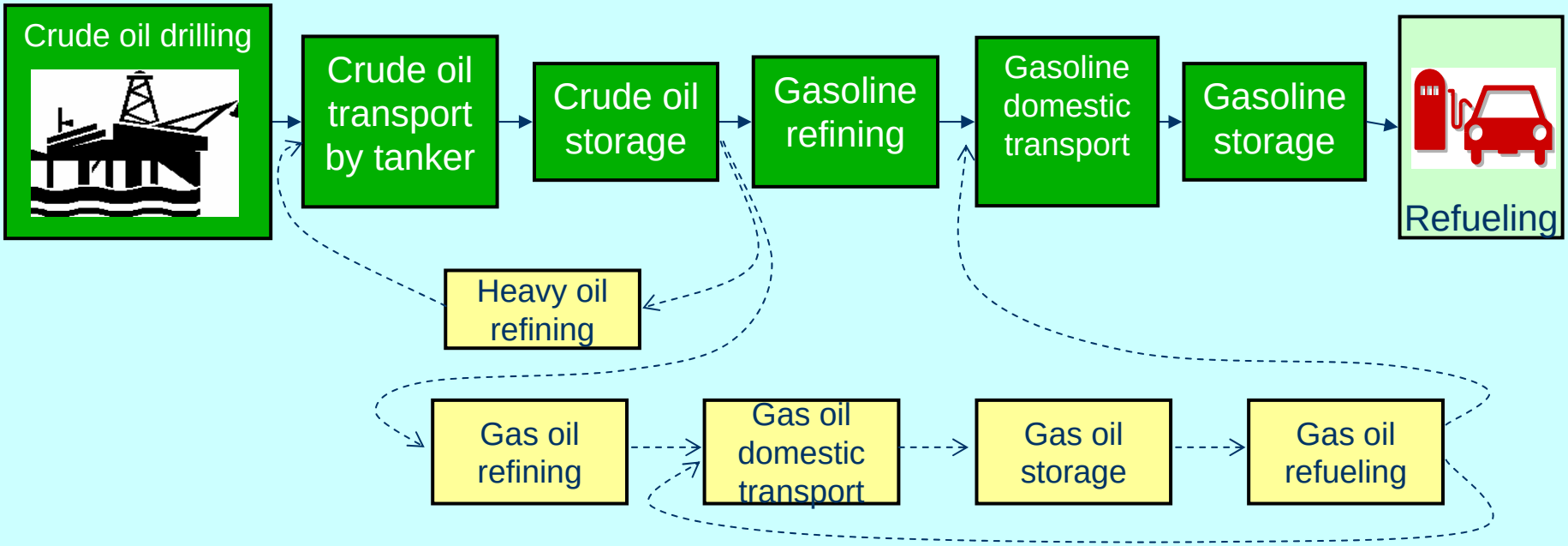
  Today, around 2010

Image of "Well to Fuel Tank" Energy Path

Efficiency

"Energy and CO2 emission" are calculated, by tracing the assumed energy path "back to the primary material in energy and fuel flow" based on the all interrelations

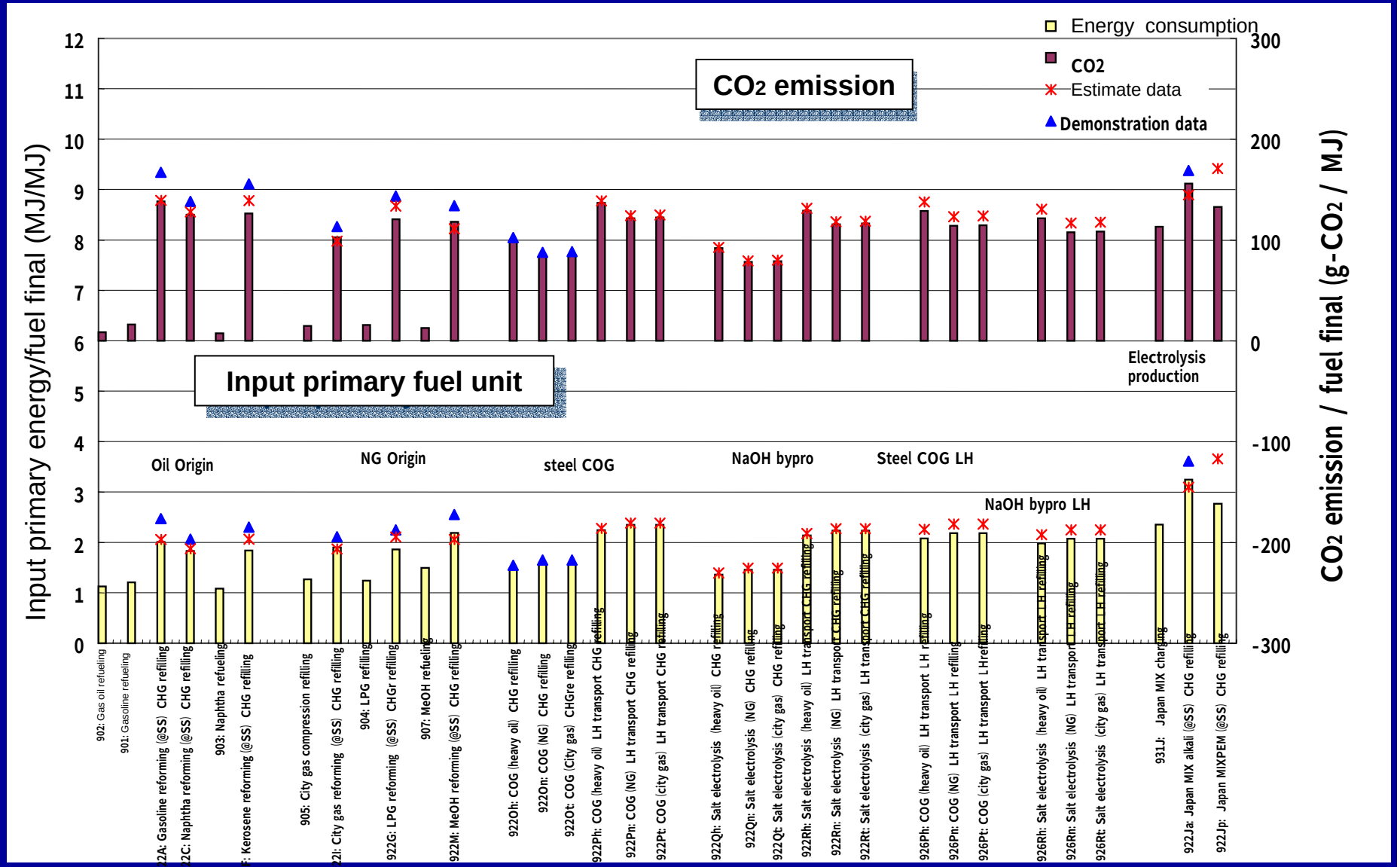
Ex. Gasoline fuel



As a standard case, 83 paths, most of which are JHFC project-related, are calculated based on published data.

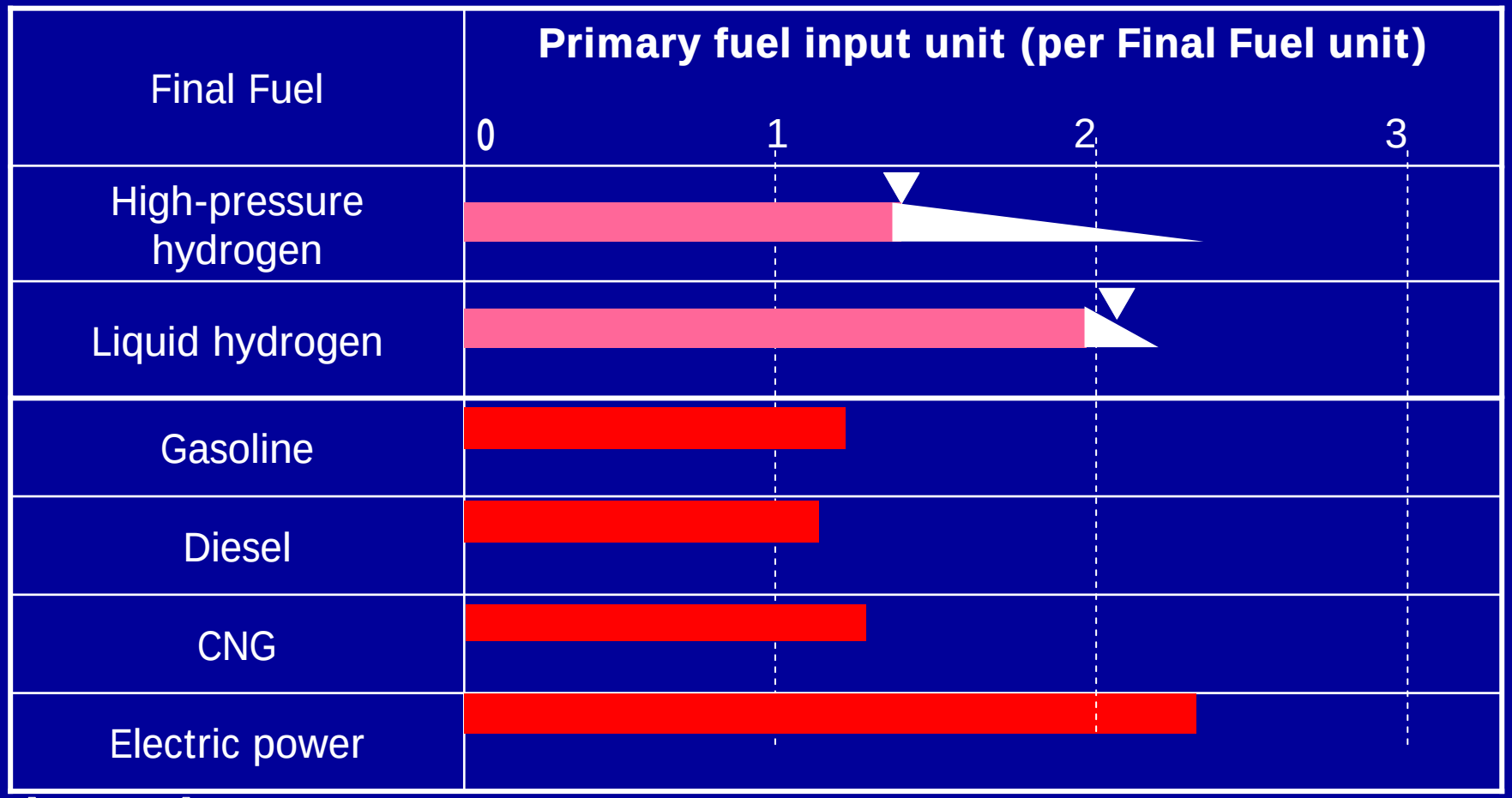
"Well to Fuel Tank" Calculation Results

Efficiency



"Well to Fuel Tank" Calculation Results Summary (Efficiency)

Efficiency



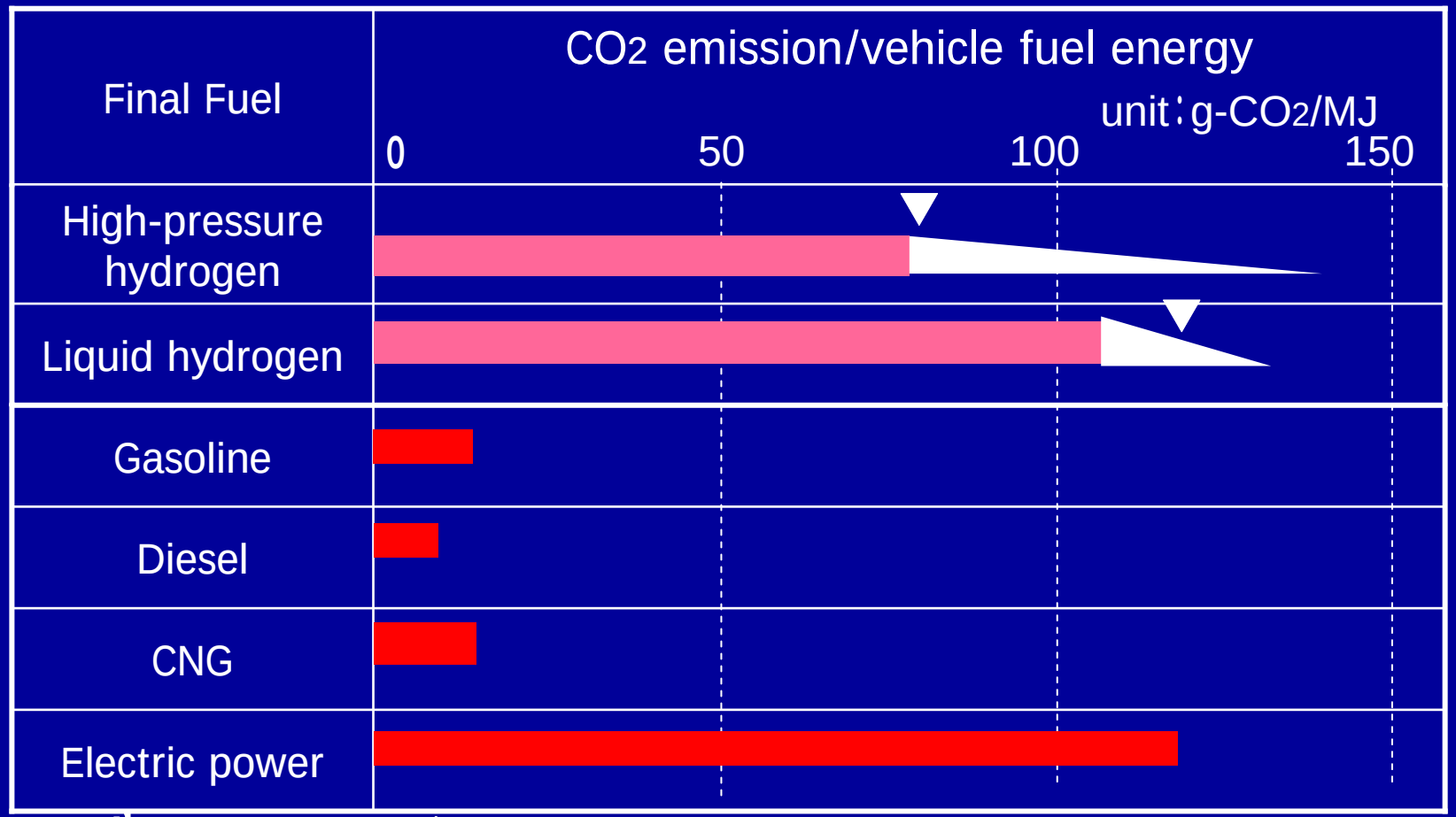
【Legend】 ┆Published data ▼┆ JHFC estimation top data

Hydrogen energy (LHV)=120MJ (1 atm .,25℃)

Electric power sources: average in Japan ***Hydrogen path: excl. electrolysis path***

"Well to Fuel Tank" Calculation Results Summary (CO_2)

Efficiency



Hydrogen energy (LHV)＝120MJ (1 atm.,25℃)

Electric power sources: average in Japan

Hydrogen path: excl. electrolysis path

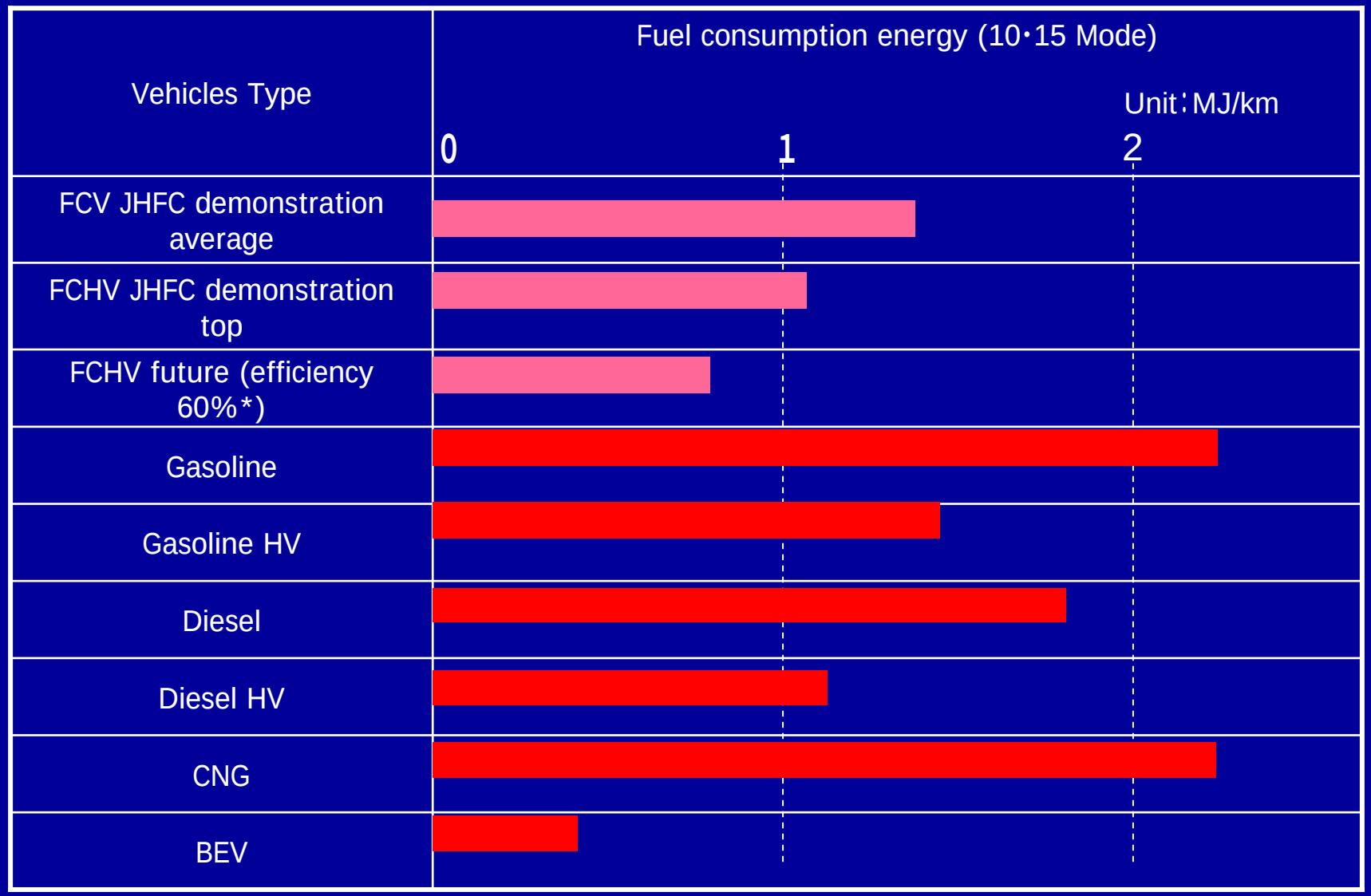
Efficiency / CO_2 Emissions Analysis

"Fuel Tank to Wheel"

"Fuel Tank to Wheel" calculation criteria

- Type of Vehicles
  Pure hydrogen (compressed, liquid), Reforming type passenger cars (excl. truck, bus)
- Vehicles for comparison
  Gasoline ICES, Diesel ICEs, Hybrid cars, CNGV, BEV
- Target year for calculation
  Current technology for "internal combustion engine, hybrid, electric vehicles" and basically around 2005-2010 technology for "FCV"
- Major preconditions on vehicle performance
  - Adopt the same vehicle performance, types and other aspects (exceptions: driving mileage of EVs, etc.)
  - Adopt the same vehicle weight of the common components (For FCVs, weights of FC-specific (different from ICEVs) are added as a basic weight)

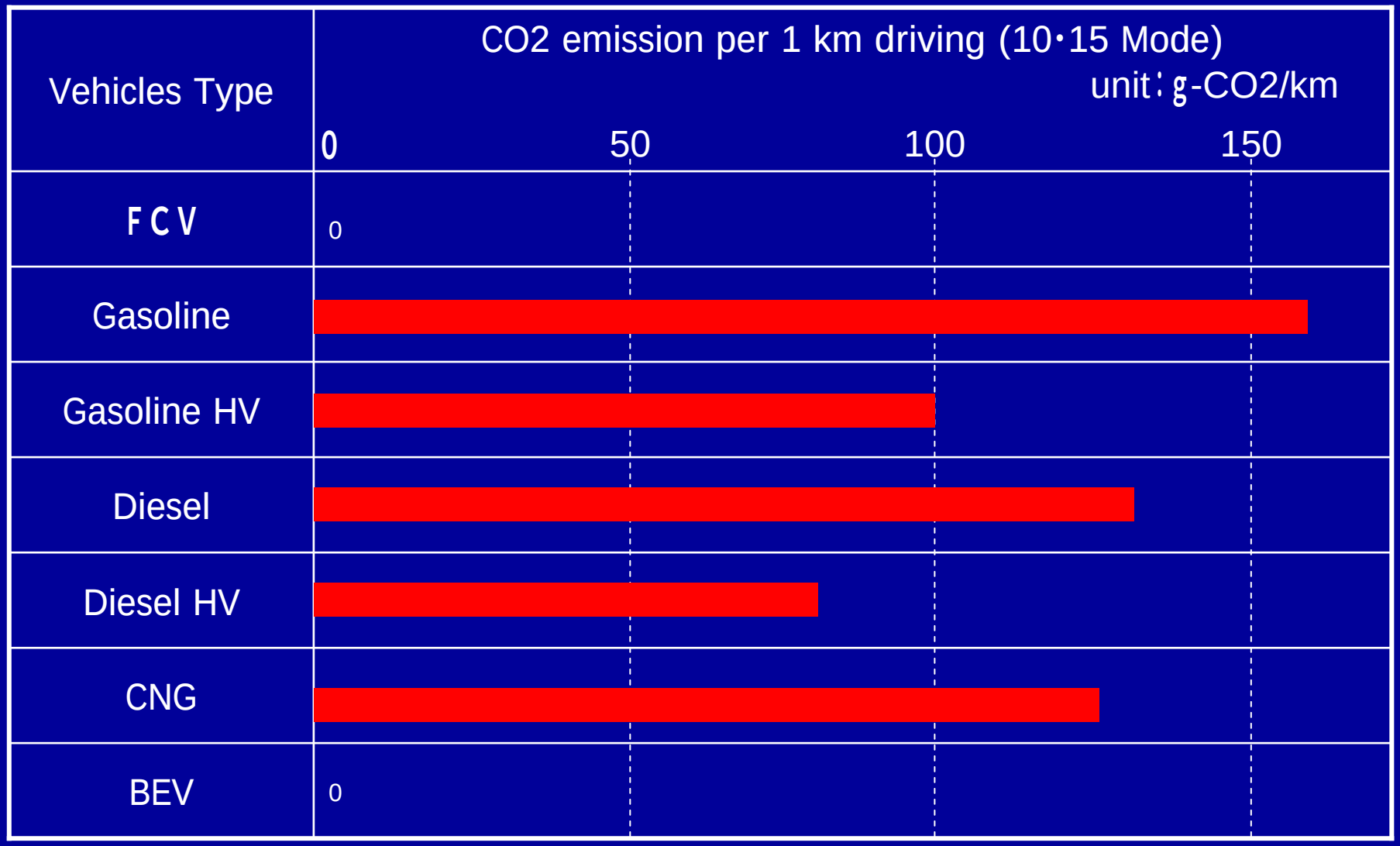
"Fuel Tank to Wheel" Calculation Results Summary(Efficiency)



* FC system efficiency

Hydrogen Energy (LHV) = 120 MJ/kg (1atm., 25℃)

"Fuel Tank to Wheel" Calculation Results (CO2)

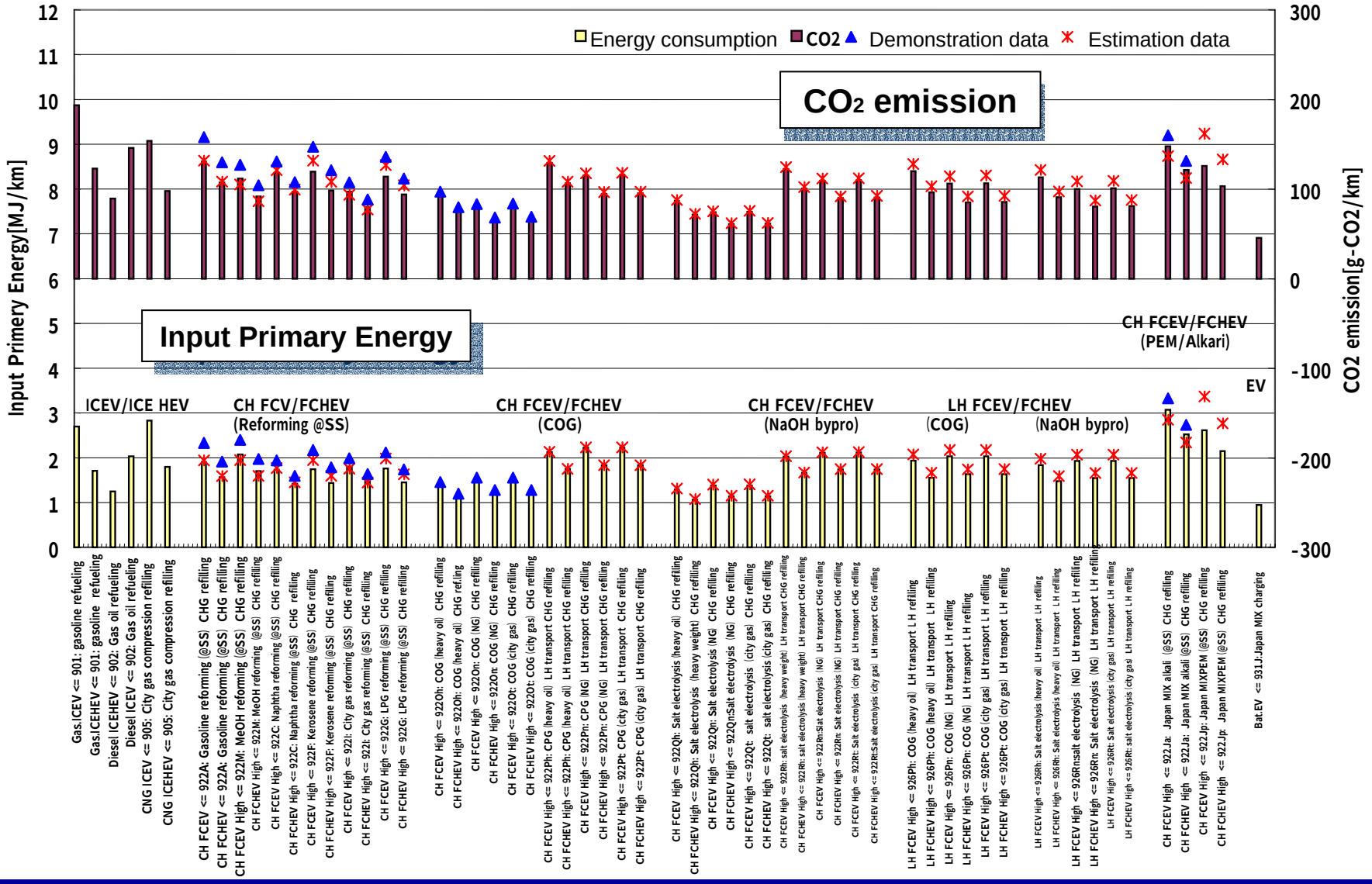


Efficiency / CO2 Emissions Analysis

“Well to Wheel”

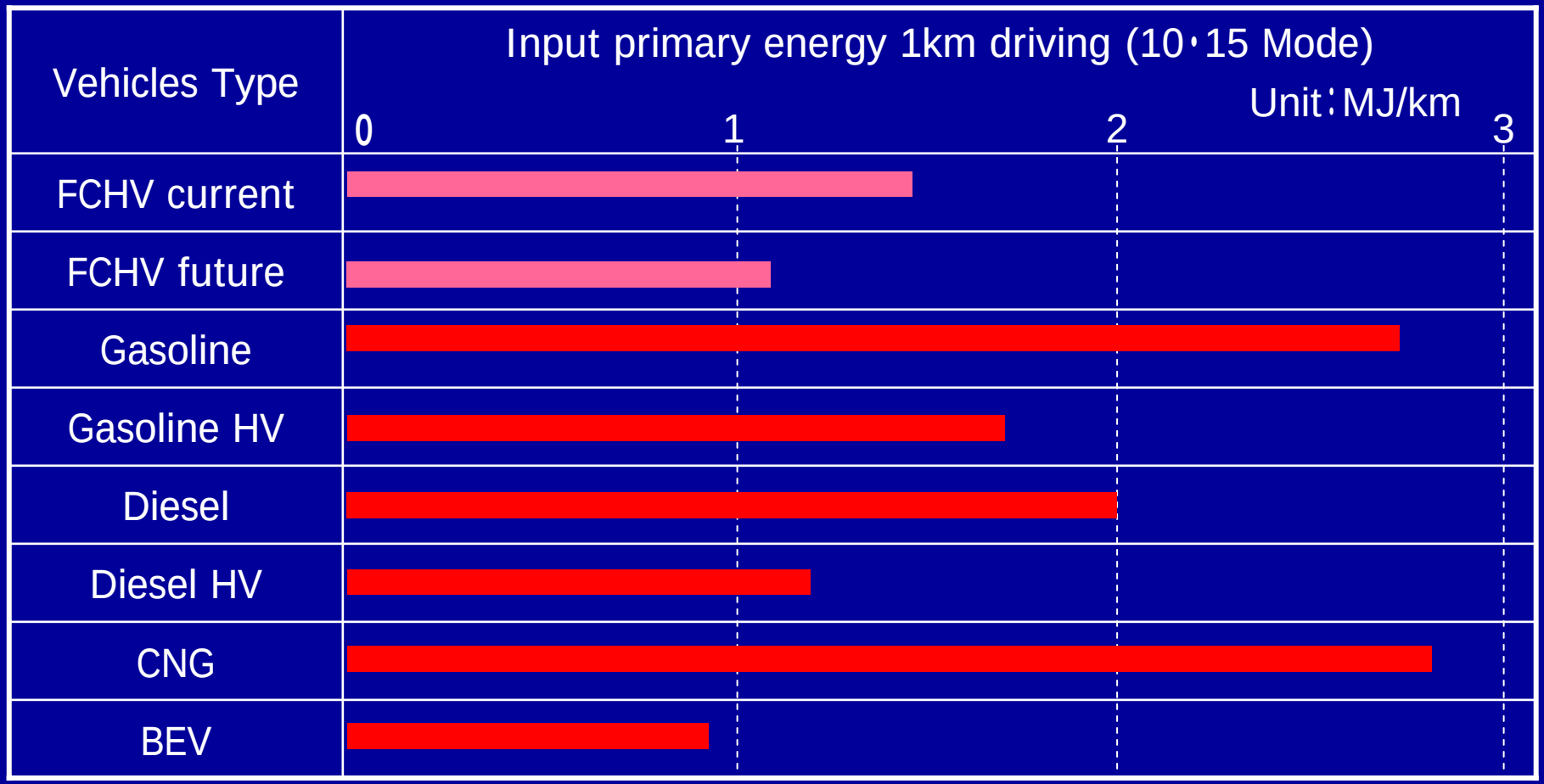
"Well to Wheel" Calculation Results

Efficiency



"Well to Wheel" Calculation Results Summary (Efficiency)

Efficiency



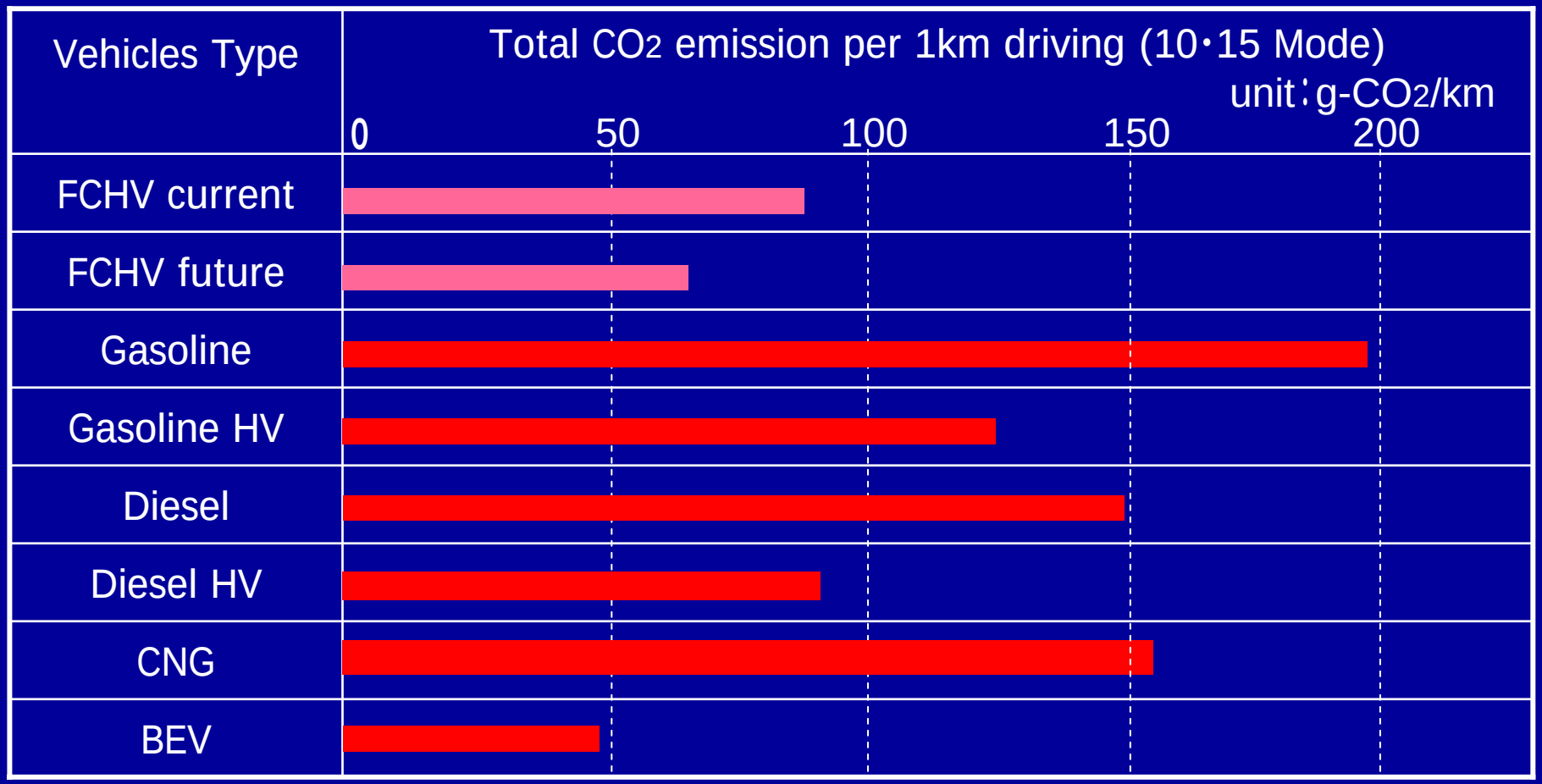
FCHV current："hydrogen station" and "FCHV" data are calculated by using JHFC demonstration top, while other data are calculated by published top.

FCHV future：calculated by using FC Stock Sys future efficiency 60% and published top.

Electric power sources: *Japan Mix*

"Well to Wheel" Calculation Results Summary (CO_2)

Efficiency



FCHV current："hydrogen station" and "FCHV" data are calculated by using JHFC demonstration top, while other data are calculated by published top.

FCHV future：calculated by using FCHV future efficiency 60% and published top.

Electric power sources: *Japan Mix*

"Well to Wheel" Analysis Results Summary

Efficiency

- Fuel cell vehicles have potential of better energy efficiency than conventional vehicles and are superior to Gasoline HV and Diesel HV both in terms of total efficiency and CO_2 emission.
- FCVS which utilized by-product gas as hydrogen source are better than other paths both in terms of required energy and CO_2 emission.
- Diesel HV has lower required energy and CO_2 emission than gasoline HV.
- Diesel HV has almost the same low required energy as FCV, but needs to lower its emission's environmental impact sufficiently, and clear PM and emission standards, to be a competitor for FCV.
- BEV is a little better than FCV both in terms of required energy and CO_2 emission, but still needs total evaluation including driving range per one charge.

Summary

Efficiency

[Achievements]

- Summarize well-to-wheel (WtW) efficiency data of various highly energy-efficient low-emission vehicles (alternative fuel vehicles), mainly of fuel cell vehicles (FCVs), with regard to Japan specific conditions, and compile collected data into **quantitative figures, objective enough to be dealt as official ones.**
- Analyze WtW efficiency and CO2 emission with current technologies, **based on JHFC demonstration data.**
- Organize Workshops on total efficiency with foreign stakeholders for opinion exchange (planned).
- Compile results of activities into a final report systematically, and publish in Japanese and English on the Web (planned).