Well-to-Wheel Efficiency Analysis

Hisashi Ishitani
Chairman, Total Efficiency Study Group
Table of Contents

- Purpose of Analysis
- Past Activities
- Concepts of Data Collection
- Study Schedule and Plan
- Status of Data Collection
- Concepts of WtW Efficiency / CO2 Emissions Analysis
- Results of WtW Efficiency / CO2 Emissions Analysis
- Summary
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
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

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 J EVA’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.
[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

**[ 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 ]**

<table>
<thead>
<tr>
<th>Toyota Motor Corp.</th>
<th>Nippon Oil Corp. Cosmo Oil Co., Ltd.</th>
<th>Nippon Steel Corp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nissan Motor Co., Ltd.</td>
<td>Show Shell Sekiyu K.K.</td>
<td>Idemitsu Kosan Co., Ltd.</td>
</tr>
<tr>
<td>General Motors Corp. (GM)</td>
<td>Iwatani International Corp.</td>
<td>Itochu Enex, Co., Ltd.</td>
</tr>
<tr>
<td>DaimlerChrysler AG</td>
<td>Taiyo Nippon Sanso Corp.</td>
<td>Babcock Hitachi</td>
</tr>
<tr>
<td>Mitsubishi Motors Corp.</td>
<td>Japan Air Gases Ltd.</td>
<td>Sinanen Co., Ltd.</td>
</tr>
<tr>
<td>Suzuki Motor Corp.</td>
<td></td>
<td>Toho Gas Co., Ltd.</td>
</tr>
</tbody>
</table>

**Total: 35 members**

**[Observers]** Ministry of Economy, Trade and Industry, NEDO, PEC

**[Secretariat]** ENAA, JARI and consultancy
Study Schedule and Plan

Efficiency

**Literature Survey**
- Interviews

**Calculation of energy efficiency**
- Energy path analysis
- Energy conversion table
- Heat value
- Data collection

**Development of Database**

**Interim report (posted on webpage)**

**Calculation using analytical tools**

**Addition of energy paths of renewable energies / biomass**

**Workshops with overseas stakeholders**
- JHFC demonstration data

**Calculation of overall Well-to-Wheel efficiency**

FY 2003:
- Energy conversion table
- Heat value
- Data collection
- Energy path analysis
- Development of Database

FY 2004:
- Addition of energy paths of renewable energies / biomass
- Calculation using analytical tools

FY 2005:
- Workshops with overseas stakeholders
- JHFC demonstration data
- Calculation of overall Well-to-Wheel efficiency
Overall Efficiency Analysis: Work Roles

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

- Hydrogen Station Data WG
- Automotive Data WG
- Data Evaluation WG

Well → Charge Tank → Fuel Tank at station → Fuel Tank at vehicle → Wheel

Overall Efficiency Analysis:

- 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

Hydrogen Station Data WG

Automotive Data WG

Data Evaluation WG

Well → Charge Tank → Fuel Tank at station → Fuel Tank at vehicle → Wheel
**Concept of Energy Path**

**Primary energies** → Exploitation → Fuel processing at producing country (Refining, liquidation) + stock storage → Long-distance transportation (e.g. by sea)

Large-scale fuel processing in Japan (refining, gasification, reforming, compression, liquidation) → domestic transportation → Fuel storage prior to hydrogen generation

On-site process (compression, reforming, liquidation) → Refueling → Fuel tank at vehicle → Vehicle operation

Charge Tank to Fuel Tank (refueling Process) → Fuel Tank to Wheel
Status of Data Collection
### Interview

<table>
<thead>
<tr>
<th>Interviewee</th>
<th>Data Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nippon Oil Corp.</td>
<td>• Information on heat value / energy efficiency of by-product hydrogen at steel plants</td>
</tr>
</tbody>
</table>
| 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                                                   |
| 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

<table>
<thead>
<tr>
<th>MJ</th>
<th>kcal (International table)</th>
<th>kcal (Measurement Law)</th>
<th>BTU</th>
<th>kl oe</th>
<th>t oe</th>
<th>kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>MJ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kcal</td>
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<td>kcal</td>
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<td>BTU</td>
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<td>kl oe</td>
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<td>t oe</td>
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<tr>
<td>kWh</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

*1 International table calorie: 4.1860X10^-3 (MJ/kcal)

*2 Measurement law calorie: 4.18605X10^-3 (MJ/kcal)
## Result II: Heat Value Table

<table>
<thead>
<tr>
<th>Unit equivalent</th>
<th>kg/ m³(nor), kg/l</th>
<th>LHV, HHV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat value</td>
<td>MJ/kg, MJ/m³(nor), MJ/l, MJ/kWh</td>
<td>LHV, HHV</td>
</tr>
<tr>
<td></td>
<td>MJ/kg equivalent</td>
<td>LHV, HHV</td>
</tr>
<tr>
<td>CO₂ emission coefficient</td>
<td>CO₂-g/MJ</td>
<td>LHV, HHV</td>
</tr>
<tr>
<td></td>
<td>CO₂-kg/kg, CO₂-kg/kWh</td>
<td>LHV, HHV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Unit conversion constant</th>
<th>Heat Value</th>
<th>Heat Value in MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>LHV</td>
<td>HHV</td>
</tr>
<tr>
<td>Coal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coking coal (Imported)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam coal (Imported)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coke</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Byproduct gas fr. ironmaking</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coke oven gas</td>
<td>kg/Nm³</td>
<td>0.470</td>
<td>MJ/Nm³</td>
<td>3.35</td>
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<tr>
<td>Blast furnace gas</td>
<td>kg/Nm³</td>
<td>1.365</td>
<td>MJ/Nm³</td>
<td>3.35</td>
</tr>
<tr>
<td>Converter gas</td>
<td>kg/Nm³</td>
<td>1.365</td>
<td>MJ/Nm³</td>
<td>3.35</td>
</tr>
<tr>
<td>Petroleum</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Result III: Efficiency Data

Energy efficiency data
Collection through published paper and others
Concepts of WtW Efficiency / CO\textsubscript{2} Emissions Analysis
Criteria for Reviewing Energy Path

- **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)
• 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.

Energy and CO2 is calculated by using the difference between "using hydrogen" and "current status."
[Energy paths Analyzed]
- Renewable Energies: solar (PV), and wind power
- No grid connection
- Solar: On-site production
- Wind: Off-site production, trucking to stations

[Energy path example: Wind]

- Electrolysis using PEM
- Alkaline water electrolysis
- Hydrogen compression
- LH2 Storage
- LH2 Transport
- Gasification of LH2
- CH2 Storage
- CH2 Transport
- Hydrogen liquefaction
- Filling
- Refueling: CH2
- Refueling: LH2
- Transport
Calculation Methodology for Biomass Fuel

[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]

1. Cultivation of Sugar cane
2. Residue of sugar cane
3. Ethanol production by Fermentation
4. Transportation by tanker
5. [Producing country]
6. [Japan]
7. Domestic transportation
8. Production of ETBE
9. Ethanol-Blended gasoline
10. Gasoline Storage
11. Refueling of ethanol-blended gasoline
12. Domestic transportation
13. ETBE-Blended gasoline
14. Gasoline Storage
15. Refueling of ETBE-blended gasoline
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 / CO₂ Emissions Analysis
Efficiency

Published Data

Well to Charge Tank

Charge Tank to Fuel Tank

Fuel Tank to Wheel

Well to Charge Tank

Charge Tank to Fuel Tank

Fuel Tank to Wheel

JHFC Demonstration Data

- JHFC Demonstrated Data
- Estimate data when commercialized

Published Data

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

Published Data

Estimates based on "the former JEVA's Activities " and "JHFC demonstration data for FCV"
"Primary energy input (MJ/km)" and "total CO2 emission (g-CO2/km)" per 1km vehicle driving are calculated, back to primary energy.

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

- **Fuel Tank to Wheel**
  - Fuel consumption energy per 1km driving (MJ/km) = b
  - Primary energy input per 1km driving (MJ/km) = a + b

- **CO2**
  - CO2 emission (g-CO2) = \( \frac{\text{CO2 emission (g-CO2)}}{\text{Fuel energy (MJ)}} \) = c
  - CO2 emission per 1km driving (g-CO2/km) = d
  - Total CO2 emission per 1km driving (g-CO2/km) = b + c + d

*This calculation uses 120MJ/kg (air pressure at 25°C) as vehicle hydrogen energy for convenience.*
Efficiency / CO2 Emissions Analysis

“Well to Fuel Tank”
“Well to Fuel Tank” Calculation Criteria

- **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
"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
### Summary (Efficiency)

<table>
<thead>
<tr>
<th>Final Fuel</th>
<th>Primary fuel input unit (per Final Fuel unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>High-pressure hydrogen</td>
<td></td>
</tr>
<tr>
<td>Liquid hydrogen</td>
<td></td>
</tr>
<tr>
<td>Gasoline</td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td>CNG</td>
<td></td>
</tr>
<tr>
<td>Electric power</td>
<td></td>
</tr>
</tbody>
</table>

### Legend
- Published data
- : JHFC estimation top data

### Hydrogen Energy
\[
\text{Hydrogen energy (LHV)} = 120 \text{MJ} (1 \text{ atm} . \text{,25})
\]

### Electric Power Sources
- average in Japan

### Hydrogen Path
- excl. electrolysis path
### "Well to Fuel Tank" Calculation Results Summary (CO2)

<table>
<thead>
<tr>
<th>Final Fuel</th>
<th>CO2 emission/vehicle fuel energy (g-CO2/MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>High-pressure hydrogen</td>
<td></td>
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<tr>
<td>Liquid hydrogen</td>
<td></td>
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<td>Gasoline</td>
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<td>Diesel</td>
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<tr>
<td>CNG</td>
<td></td>
</tr>
<tr>
<td>Electric power</td>
<td></td>
</tr>
</tbody>
</table>

#### Legend
- Published data
- JHFC estimation top data

**Hydrogen energy (LHV) = 120MJ (1 atm., 25°C)**

**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)

<table>
<thead>
<tr>
<th>Vehicles Type</th>
<th>Fuel consumption energy (10-15 Mode)</th>
<th>Unit: MJ/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCV J HFC demonstration average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCHV J HFC demonstration top</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCHV future (efficiency 60%*)</td>
<td></td>
<td></td>
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<tr>
<td>Gasoline</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline HV</td>
<td></td>
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<tr>
<td>Diesel</td>
<td></td>
<td></td>
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<tr>
<td>Diesel HV</td>
<td></td>
<td></td>
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<tr>
<td>CNG</td>
<td></td>
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<tr>
<td>BEV</td>
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<td></td>
</tr>
</tbody>
</table>

* FC system efficiency

*Hydrogen Energy (LHV) = 120 MJ/kg (1atm., 25°C)*
<table>
<thead>
<tr>
<th>Vehicles Type</th>
<th>CO2 emission per 1 km driving (10•15 Mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>unit : gCO2/km</td>
</tr>
<tr>
<td></td>
<td>0</td>
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<tr>
<td>FCV</td>
<td>0</td>
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<tr>
<td>Gasoline</td>
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<td>Gasoline HV</td>
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<td>Diesel</td>
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<td>Diesel HV</td>
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<tr>
<td>CNG</td>
<td>0</td>
</tr>
<tr>
<td>BEV</td>
<td>0</td>
</tr>
</tbody>
</table>
Efficiency / CO2 Emissions Analysis
“Well to Wheel”
"Well to Wheel" Calculation Results

- **Energy consumption**
- **Demonstration data**
- **Estimation data**

**Input Primary Energy**

**CO₂ emission**
"Well to Wheel" Calculation Results Summary (Efficiency)

<table>
<thead>
<tr>
<th>Vehicles Type</th>
<th>Input primary energy 1km driving (10・15 Mode)</th>
<th>Unit MJ/km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>FCHV current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCHV future</td>
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<tr>
<td>Gasoline</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline HV</td>
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<tr>
<td>Diesel</td>
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<td>Diesel HV</td>
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<tr>
<td>CNG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BEV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 (CO2)

<table>
<thead>
<tr>
<th>Vehicles Type</th>
<th>Total CO2 emission per 1km driving (10-15 Mode) unit g-CO2/km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>FCHV current</td>
<td></td>
</tr>
<tr>
<td>FCHV future</td>
<td></td>
</tr>
<tr>
<td>Gasoline</td>
<td></td>
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<tr>
<td>Gasoline HV</td>
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<tr>
<td>Diesel</td>
<td></td>
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<tr>
<td>Diesel HV</td>
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<tr>
<td>CNG</td>
<td></td>
</tr>
<tr>
<td>BEV</td>
<td></td>
</tr>
</tbody>
</table>

**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*
**Efficiency**

"Well to Wheel" Analysis Results

Summary

- 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 CO2 emission.

- FCVS which utilized by-product gas as hydrogen source are better than other paths both in terms of required energy and CO2 emission.

- Diesel HV has lower required energy and CO2 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 CO2 emission, but still needs total evaluation including driving range per one charge.
Summary

[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 J HFC 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).