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Cost Estimation of Transported Hydrogen, Produced by Overseas Wind Power Generations

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1 Introduction

Japan is striving to spread the use of nuclear and renewable energy, yet still continues to be highly dependent on fossil fuel. This sort of energy supply-demand structure carries significant risks from foreseeable future resource and environmental restrictions. Therefore, it will be very important in the future to establish a social system that can consistently import or produce a set amount of resource supplies without green house gas emissions. In this study, we developed a concept for a global hydrogen energy system using wind power generation as a hydrogen source, investigated its economic efficiency, compared it with power generating fuels used at existing thermal power plants, and examined the feasibility of the global hydrogen energy system.

2 System Concept

Figure 1 shows a conceptual diagram of a system to import wind power generated in overseas regions with favorable climatic conditions into Japan.

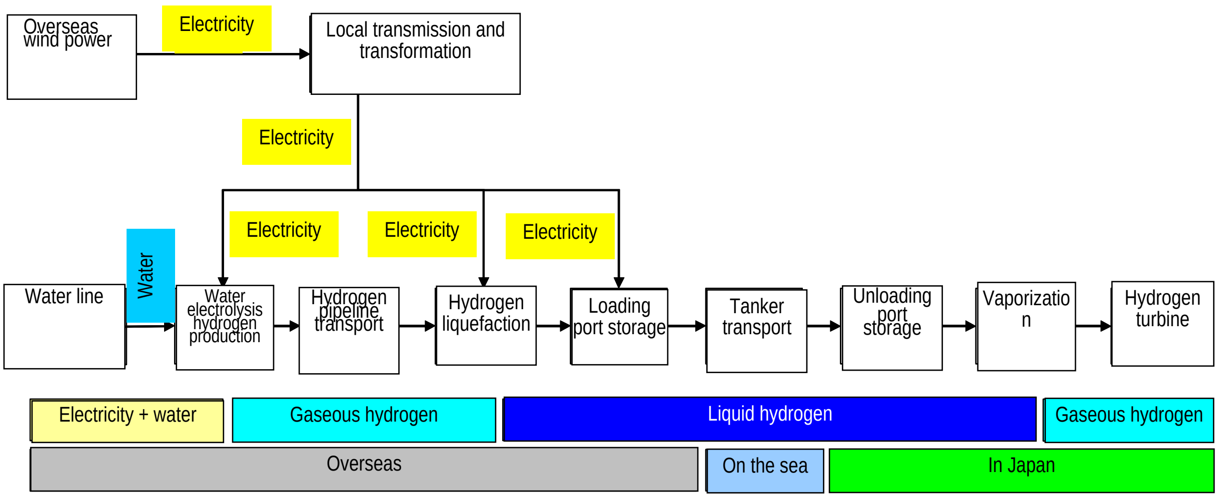

Figure 1: Conceptual diagram of overseas wind-hydrogen system.

Overseas wind energy will fuel domestic steam power plants. Component systems leading to domestic electricity power supply are shown in Figure 1. “Local transmission and transformation” is a system which supplies electricity for “water electrolysis hydrogen production,” “hydrogen liquefaction” to liquefy gaseous hydrogen transported, and utility “loading port storage” at a liquid hydrogen loading and storage base. “Water line” is a system which supplies water from nearby rivers to use as hydrogen source material in “water electrolysis hydrogen production." "Hydrogen production" and "hydrogen liquefaction" are connected via hydrogen pipelines. Liquid hydrogen will be loaded on to tankers, shipped to Japan, and supplied to domestic power plants. This system leading to domestic hydrogen supply is similar to importing liquefied natural gas (LNG).

3 Feasibility Study of Overseas Wind Energy Import

3.1 Cases to study

As shown in Table 1, three cases were examined.

Table 1: Cases to study.

	Equipment Scale	Energy Efficiency
Case (1)	Existing equipment	Present case
Case (2)	Larger equipment	Present case
Case (3)	Larger equipment	Future case

Existing equipment is assumed to have capacities that are already being utilized as products in the world (e.g. storage tank capacity estimated at 3,000m^3). Larger equipment is assumed to have larger capacity, to take cost advantages into account (e.g. storage tank capacity estimated at 80,000m^3).

Present cases of energy efficiency assume the electric power consumption rate for water electrolysis hydrogen production and hydrogen liquefaction to be at present levels. Future case assume an improved electric power consumption rate over present levels.

3.2 Assumed wind power plant construction site

Based on the report [1] prepared by the investigation team of the Hydrogen Energy Systems Society of Japan (HESS), it is predicted that the overseas wind power station would be constructed north of the city of Pico Truncado, in the state of Santa Cruz in Southern Patagonia, Argentina.

In Southern Patagonia, it is assumed that windmills can be used in 50% of its 469,000km^2 area. Its wind energy potential is said to be ten times Japan's electricity demand [2, 3]. For the purpose of this study, the domestic transmission side electric energy was set to approx. 10% (8.9 ×1010kWh/year) of the electricity sold by ten Japanese power companies in FY2006. To cover this much electricity in Patagonia, 340 billion kWh/year for present cases (at current levels of electric power consumption rate for water electrolysis hydrogen production and hydrogen liquefaction) or 265 billion kWh/year for future cases needs to be generated, which would account for 3 to 4% of the 9.6 trillion kWh/year potential electricity generated in Patagonia.

3.3 Overseas wind power generation

(1) Annual Capacity Factor

The HESS investigation report [1] estimates that the capacity factor of wind power generation in Santa Cruz will be 49%, taking into account maintenance outages and miscellaneous losses. In this study, the annual capacity factor was set to 50% as shown in Equation (1).

$$\text{Annual capacity factor (\%)} = \frac{\text{Annual output} \times 100}{\text{Rated output} \times 8{,}760} \quad (1)$$

(2) Unit Price and Number of Windmills Installed

The unit price of windmill construction was calculated based on the data published by the U.S. National Renewable Energy Laboratory (NREL) [4, 5]. According to NREL published data, the construction unit price of a windmill at 1.5MW rated output, 70m rotor diameter, and 65m hub height is calculated at US$981/kW. The maximum rated output is 5MW [6] for current commercial windmills. In this study, however, it is assumed that Case (1) will use a windmill at 3MW rated output, 99m rotor diameter, and 65m hub height, while Case (2) or (3) will use a windmill at 5MW rated output, 99m rotor diameter, and 65m hub height. Based on the NREL unit price.

As a result, the construction unit price of the 3MW windmill for Case (1) was estimated at US$1,031/kW, and the 5MW windmill for Cases (2) and (3) at US$859/kW.

By using Equation (1), the rated power generating capacities, the number of windmills installed, and their construction costs were obtained as shown in Table 2 for the wind farm to be constructed in Patagonia.

Table 2: Rated power generating capacities, windmills, and construction costs for wind power generation.

	Capacity (MW)	Windmills (Units)	Construction Cost (million US$)
Case (1)	77,500	25,800	80,000
Case (2)	77,500	15,500	66,600
Case (3)	60,400	12,100	51,900

3.4 Local transmission and transformation

For a wind farm to supply wind energy for “water electrolysis hydrogen production,” “hydrogen liquefaction,” and “loading port storage,” a rated electric power of approx. 1,500MW and 500 windmill units are required for Case (1), and 300 units for Cases (2) and (3).

The number of wind farms to construct and the scale of each location are shown in Table 3.

Table 3: Number of wind farms to construct and scale of each location wind farms.

	Wind Farms (Locations)	At Right Angle to Wind Direction (km)	Parallel to Wind Direction (km)
Case (1)	52	15	10
Case (2)	52	9	10
Case (3)	41	9	10

Using the substation construction unit price presented in the Electric Technology Research [7], as well as Reference 9 [8] of the Working Group on Electric Power Equipment and Electromagnetic Fields for reference, the cost for local transmission and transformation per wind farm was estimated at US$500 million. The total construction cost for local transmission and transformation was calculated at US$26.4 billion for Case (1), US$25.6 billion for Case (2), and US$20.2 billion for Case (3).

3.5 Examination of Electric Power Required and Capacity Factor

(1) Relationship between Rated Output and Capacity Factor

The relationship between rated output and capacity factor was calculated based on the following assumptions:

Assumption 1: All output from wind power generation will be used for "water-electrolysis hydrogen production," "hydrogen liquefaction," and "loading port storage."

Assumption 2: The amount of liquefied hydrogen reflects losses that may occur before produced hydrogen arrives for liquefaction.

Equations (2) and (3) can be worked out from Assumption 1, and Equation (4) from Assumption 2.

When the relationship between Gt×G, Lt×Lm, and Wt×Wm is obtained based on the above relational Equations, Equations (2) and (3) can be worked out.

$$Gt \times Gm = \alpha/(\alpha + \beta(1 - \delta)) \times (1 - \gamma) \times Wt \times Wm \quad (2)$$

$$Lt \times Lm = \beta(1 - \delta)/(\alpha + \beta(1 - \delta)) \times (1 - \gamma) \times Wt \times Wm \quad (3)$$

Where,

Wt: Rated output from wind power generation (kW)

Gt: Rated power for water electrolytic hydrogen production (kW)

Lt: Rated power for liquefaction (kW)

Wm: Capacity factor of wind power generation (%)

Gm: Capacity factor of water electrolytic hydrogen production (%)

Lm: Capacity factor of hydrogen liquefaction (%)

α: Electric power consumption rate for hydrogen production (kWh/Nm3)

β: Electric power consumption rate for liquefaction (kWh/Nm3)

δ: Loss until arrival for liquefaction/hydrogen produced by water electrolysis

γ: Electric power used for loading port storage/generated output ( )

(2) Percentages of Generated Output Used for Water Electrolysis Hydrogen Production and Hydrogen Liquefaction

The percentages of generated output used for water electrolysis hydrogen production Pg (%) and hydrogen liquefaction Pl (%) can be obtained by Equations (4) and (5), based on Equations (2) and (3).

$$Pg = (Gt \times Gm)/(Wt \times Wm) \times 100 = \alpha/(\alpha + \beta(1-\delta)) \times (1-\gamma) \times 100 \quad (4)$$

$$Pg = (Gt \times Gm)/(Wt \times Wm) \times 100 = \alpha/(\alpha + \beta(1-\delta)) \times (1-\gamma) \times 100 \quad (5)$$

The percentages of generated output used for hydrogen production and liquefaction are independent of the scale and capacity factor of wind power generation.

Next, assuming that the electric power consumption rates of hydrogen production and liquefaction are for present cases (applicable to Cases (1) and (2)) [9] and for future cases (applicable to Case (3)) [10], the percentages of generated output used for hydrogen production and liquefaction are shown in Table 4.

Table 4: Percentages of generated output by electric power consumption rate.

	Present Case	**Future Case**
Hydrogen production power consumption rate	4.77 kWh/Nm^3	4.05 kWh/Nm^3
Hydrogen liquefaction power consumption rate	1.20 kWh/Nm^3	0.6 kWh/Nm^3
Pg	79.2%	86.3%
Pl	19.8%	12.7%

3.6 Water line

Water used for water electrolysis hydrogen production will be taken from the Desead River, near the wind farm construction site. The water line will be composed of a main pipe to supply water from the water source, and branch pipes within the farm. The length and bore diameter of the main pipe will be approx. 213km and 1,400mm respectively for Case 1, and 153km and 1,400mm for Cases 2 and 3. Assuming that the length of a branch pipe is approx. 10km, the total length and bore diameter of branch pipes will be 515km and 500mm respectively for Cases 1 and 2, and 406km and 500mm for Case 3. Based on interviews with experts, the ratio of material costs, ancillary equipment including pumps, and installation costs was assumed to be 30:30:40. The water line construction cost was estimated at approx. US$1,540 million for Case (1), US$1,260 million for Case (2), and US$1,140 million for Case (3).

3.7 Water electrolysis hydrogen production

Based on the annual total hydrogen production of 54 billion Nm^3/year and hydrogen production capacity of approx. 13.5 million Nm^3/h is required for Cases (1) and (2), and 13.0 million Nm^3/h for Case (3).

3.8 Hydrogen pipeline transport

The arrangement of the hydrogen pipelines installed between the water electrolysis hydrogen production systems.

Table 5: Length and construction cost of hydrogen pipelines.

	Pipeline Length (km)	Construction Cost (US$-in million)
Case (1)	1,290	640
Case (2)	980	490
Case (3)	770	390

3.9 Hydrogen liquefaction

The maximum capacity of existing liquefaction equipment is approx. 50 to 60 tons/day. The per-unit liquefaction capacity was set at 51 tons/day for Case (1). Since the larger equipment for Cases (2) and (3), would require an enormous liquefaction capacity (approx. 16,400 tons/day), the per-unit liquefaction capacity was set to 300 tons/day based on the conceptual design [11] implemented by the World Energy Network (WE-NET). Based on the estimation [12] performed by a European liquefaction equipment manufacturer, the construction cost of a 300 tons/day unit was calculated at approx. €199.5 million (approx. US$245 million using the exchange rate of US$1.23 to an Euro), with a 51 tons/day unit calculated at approx. US$75 million using the 2/3 power law. As a result, it was estimated that 322 units would be required for Case (1) at construction cost of approx. US$24.3 billion while 55 units would be required for Cases (2) and (3) at construction cost of US$13.5 billion.

3.10 Loading port storage and unloading port storage

Storage facilities will be constructed at liquid hydrogen loading and unloading bases. Assuming the loading port can hold 1/24th or 14 day's worth of the annual liquid hydrogen discharge amount, and the unloading port can hold 1/12th or 30 day's worth of domestically generated electricity, a storage capacity of approx. $2.6\times10^6 m^3$ will be required at the loading port and $5.0\times10^6 m^3$ at the unloading port. Since the largest liquid hydrogen storage facility (held by NASA) is approx. $3,000 m^3$, the capacity of a single tank for Case (1) was set to $3,000 m^3$. For Cases (2) and (3) involving larger equipment, it was set to $80,000 m^3$/unit, based on the conceptual design of a $50,000 m^3$-class liquid hydrogen storage system implemented by WE-NET.

After consulting with experts, the construction unit price of an 80,000m3 unit was estimated at US$240 million, and we estimated the price of a 3,000m3 unit at US$27 million using the 2/3 power law.

It was ultimately estimated that for Case (1), 866 units would be required at the loading port at construction costs of US$23.300 billion, while 1,670 units would be required at the unloading port at construction costs of US$44.9 billion. For Cases (2) and (3), 33 units will be required at the loading port at construction costs of US$7.9 billion, while 63 units will be required at the unloading port at construction costs of US$15.1 billion.

3.11 Tanker transport

The shipping distance from the loading storage base to the unloading storage base is approx. 20,000km. Liquid hydrogen may be transported in containers, barges, or tankers, but shipping liquid hydrogen has not yet been commercialized. Therefore, we had to estimate tanker capacity at 12,000m^3/tanker for Case (1) and 63,000m^3/tanker for Cases (2) and (3), using the liquid hydrogen tanker conceptual design [11] based on WE-NET LNG tanker technology as reference. Assuming that the construction unit price of a 63,000m^3 tanker is US$248 million, the price of a 2,000 m^3 tanker was calculated at US$82 million using the 2/3rds law. Assuming tanker speed of 19.5 knots (approx. 36.1km/h) at 7 round trips per year, it is estimated that 807 tankers will be required for Case (1) at construction cost of US$66.3 billion, while 154 tankers will be required for Cases (2) and (3) at construction cost of US$38.2 billion.

3.12 Vaporization

It is estimated that a vaporization capacity of approx. 12 thousand tons/day will be required, based on the annual total hydrogen vaporization capacity of 4.3 million tons/year. Assuming that the same capacity is applicable for Cases (1) through (3), the carburetor capacity and capacity factor were calculated at 8 tons/h and 80%, respectively. The construction unit price was calculated at US$1.4 million/unit based on the DOE review [13]. As a result, it was estimated that 24 units would be required at construction cost of US$109 million.

3.13 Hydrogen turbine power generation

In order to achieve 60% generating efficiency (HHV), WE-NET examined major components of the hydrogen turbine, such as turbine blades and rotors. Specifications for turbine capacity, equipment cost, generation-side efficiency, and capacity factor were drawn up based on WE-NET achievements [11]. For Cases (1) through (3), it is estimated that a total of 33 turbines will be required at a total rated output of to 16.5 GW (500MW x 33 units) and construction costs of US$15.4 billion.

4 Prerequisites for Feasibility Study

The operating period will be 30 years and the equipment will continue to be used even after the statutory depreciation period (e.g. 17 years for wind power generation). For water electrolysis hydrogen production and hydrogen liquefaction, however, the equipment will be upgraded once (in Year 16). Table 6 shows the statutory service life of each component system.

Table 6: List of annual expenses of each component system.

Component System	Statutory Service Life (years)	Repair Expenses (%)
Overseas wind power generation	17	1.0
Local transmission / transformation	22	2.0
Water line	18	2.0
Water electrolysis hydrogen production	10	2.0
Hydrogen pipeline transport	22	2.0
Hydrogen liquefaction	10	3.0
Loading port storage	10	3.0
Tanker transport	15	2.0
Unloading port storage	10	3.0
Vaporization	15	2.0
Hydrogen turbine	15	4.0

5 Feasibility Study Results

5.1 Total cost

Figure 2.1 show the total costs for Cases (1) and Figure 2.2 show the total costs for Cases (3). The total costs were obtained by Equation (6).

Total cost = construction cost with interest + 30-year variable expenses (15)

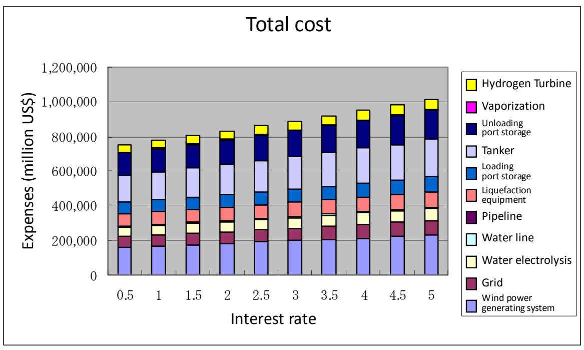

Figure 2.1: Construction cost (case (1)).

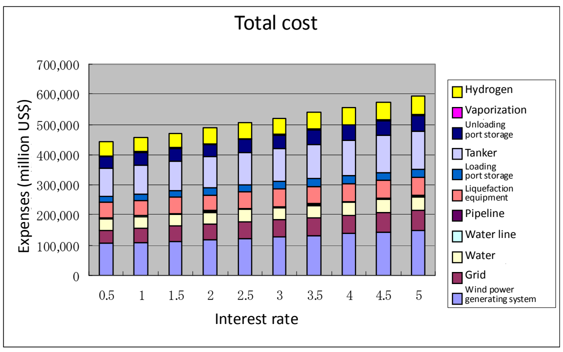

Figure 2.2: construction cost (case (3)).

The construction cost in Case 1 was estimated at approx. US$750 billion with a 0.5% interest and approx. US$1 trillion with a 5% interest. However in Figure 5.1.2, the construction cost in Case 3 was estimated to be much lower at approx. US$ 450 billion with a 0.5% interest and approximately US$ 600 million with a 5% interest.

5.2 Electricity Price

(1) Electricity Price by Case

The plant transmission side electricity price (cent/kWh) for electricity fueled by hydrogen from overseas wind power generation was calculated, with results shown in Figure 3.1 and Figure 3.2.

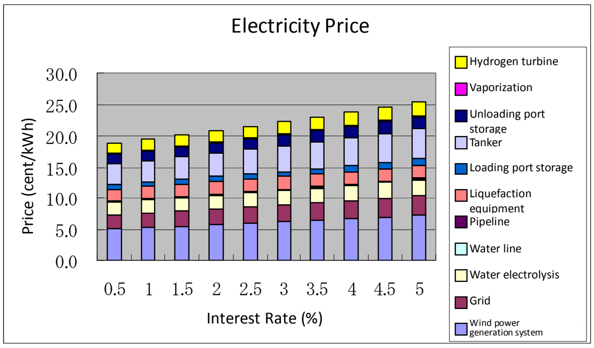

Figure 3.1: Electricity price (case (1)).

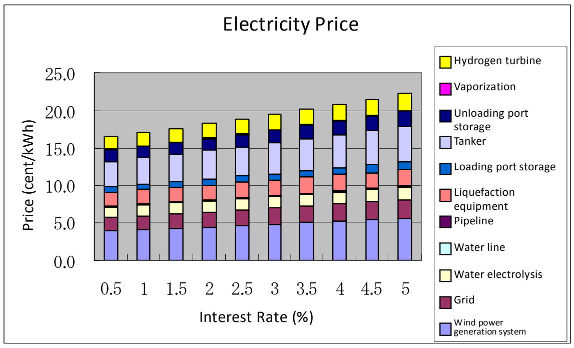

Figure 3.2: Electricity price (case (3)).

(2) Comparison of Unit Electricity Price with Thermal Power Plant

The prices of fossil fuels were obtained by dividing the fuel import CIF prices (monthly average) published in the Trade Statistics of Japan [14] by their respective calorific values (heavy oil: 41.9MJ/liter, LNG: 54.6MJ/kg, coal: 25.7MJ/kg) [15]. Figure 4 shows the relationship between the hydrogen turbine plant transmission side electricity price of hydrogen turbine power generation calculated in 5.2 and the fuel expenses of the existing thermal power plant.

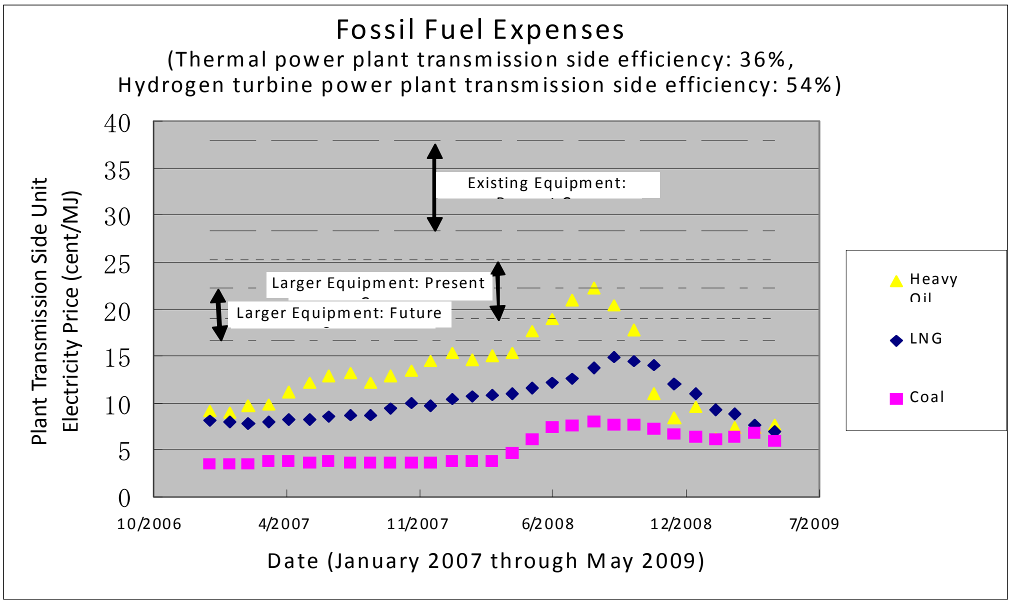

Figure 4: Calorimetric comparison of hydrogen from overseas wind power generation and fossil fuels.

It was found that the construction of a new hydrogen turbine plant would be economically justified when import prices for heavy oil and LNG were close to the 2008 peak values. During that period, the monthly CIF price was US$ 850 to 930 /kl for heavy oil and US$660 to 810/ton for LNG, while the WTI value averaged US$100 to 133/barrel. The Energy Supply and Demand Subcommittee of the Advisory Committee for Natural Resources and Energy recalculated its long-term energy supply and demand outlook, estimating crude oil prices would be US$ 121/barrel in 2020 and US$ 169/barrel in 2030 [16]. This study suggests that electricity stemming from overseas wind power generation may have economic efficiency compared with existing thermal power generation by around 2020 to 2030.

6 Conclusion

It is difficult for hydrogen stemming from overseas wind power generation to show economic efficiency in terms of calorific value compared to present fossil fuel prices. It has sufficient economic efficiency over byproduct hydrogen produced at factories. It is suggested that in the future, it would be more effective to decommission existing oil-fired thermal power plants and construct new hydrogen turbine plants.

Finally, we would like to extend our appreciation to those who provided their wisdom and advice on this study.

References

[1] NEDO; Investigation Report on the “Investigation on Hydrogen Production Using South American Renewable Energy,” (2006)

[2] Yukio Suguro; Potential of Windmill Utilization in Argentina, 6th Wind Energy Utilization General Seminar of Ashikaga Institute of Technology (2006)

[3] Kenji Murata: Patagonia in Argentina Famous for Wind, Seasonal Report, Institute of Applied Energy, Vol. 29, No. 2 (2006), 98-106

[4] NREL; Baseline Cost of Energy (Date of Access: 2008.4.14) http://www.nrel.gov/wind/coe.html

[5] The following sheets contained in 4) were used: - Example COE Projection Sheet - Annual Energy Production Calculator (MS Excel 253KB)

[6] REpower; WEB (Date of Access: 8/5/2008) http://www.repower.de/index.php?id=1&L=1

[7] Electric Technology Research; “Technologies to Expand the Dissemination of 20kV-class/400V Distribution Systems,” Electric Technology Research Vol. 56, No. 3, (2000), 287

[8] Nuclear and Industrial Safety Subcommittee, Subcommittee on Electric Power Safety; “Working Group on Electric Power Equipment and Electromagnetic Fields,” Reference 9, (2008), NEDO, Fuel Cell and Hydrogen Technology Development Department; 2005 Fuel Cell and Hydrogen Technology Development Roadmap, (2006)

[10] DOE Hydrogen Program; Well-to-Wheels Analysis, 39.

[11] NEDO; International Clean Energy System Technology Using Hydrogen Subtask 3 Total System Conceptual Design, (1999)

[12] E4tech; The Economics of a European Hydrogen Automotive Infrastructure, A study for Linde AG, (2005)

[13] DOE; 2008 DOE Hydrogen Program Review Hydrogen Delivery Infrastructure Analysis, (2008), 6

[14] Trade Statistics of Japan Homepage; http://www.customs.go.jp/toukei/info/index.htm (Date of Access: 2009.8.17)

[15] Agency for Natural Resources and Energy; Standard Calorific Value Review Results and Revised Values Applicable in and after FY2005, (2007)

[16] Energy Supply and Demand Subcommittee, Advisory Committee for Natural Resources and Energy; Long-Term Energy Supply and Demand Outlook (Recalculated) (Draft), (2009)