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An Energy Supply Chain from Large Scale Photovoltaic Power Generation from Asian Cities to End Users in Japan

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Abstract

This study proposes four possible energy supply chains from the megawatt class of photovoltaics (PV) installation in Kuala Lumpur, Kolkata, Beijing or Ulan Bator to end users in Tokyo Japan. In the proposed chains, the electricity generated from solar PV panels would be used to generate H_2 through water electrolyzer. The H_2 is then liquefied (or converted into organic hydride) and transported by tank truck for land as well as tanker for marine to Japan and finally supplied to fuel cells (FC) for power generation purpose. This study investigates the energy efficiencies of the proposed energy supply chain and the amount of CO_2 emission in the transportation process from the four locations. As a result, it is found the largest amount of power could be generated in Ulan Batorthan in other cities with the same size of solar panel array, while it also emitted the largest amount of CO_2 in the transportation process. The best energy efficiency is obtained in the case of Beijing. This study also revealed that the ratio of total energy consumption to calorific value of H_2 after transportation in the case of H_2 liquefaction is smaller than that in the case of organic hydride.

Keywords

Energy Supply Chain, Photovoltaics, H_2 Produced by Water Electrolysis, Energy Transportation

1. Introduction

Fossil fuel reserves are limited and intensive burning of hydro-carbon based fuel sources is impacting on global climate. Renewable energy sources such as wind, solar photovoltaic (PV), solar thermal, geothermal, bio-energy are drawing attention as alternative environment-friendly energy sources [1]. However, the energy density of these renewable energy sources is low. Most of them are dependent on nature and have intermittent characteristics. Therefore, it is very important to develop proper strategies and technologies to integrate these renewable energy sources into the power system network in order to fulfill the energy demand [1].

It was proposed that photovoltaics or wind turbine would be installed oversea where a good solar radiation and wind condition are obtained and the power generated by photovoltaics and wind turbine are converted into H_2 by water electrolysis using the generated power and transported to Japan [2] [3]. If large renewable energy is produced in high potential area and transported to Japan, the energy demand would be fulfilled well. Therefore, this study proposes the energy supply chain consisting of large scale photovoltaics installed in several Asian cites which have a better solar radiation than Japan, water electrolysis for H_2 production and transportation by tank truck for land as well as tanker for marine. Since gases H_2 at atmospheric pressure is not suitable for transportation and storage due to low energy density, this study assumes to transport H_2 produced by water electrolysis to Japan by means of liquefied H_2 or organic hydride.

Due to solar energy's intermittent nature, the typical energy storage system in associated with normal PV systems such as battery bank and hydrogen produced by water electrolysis produced by the power of PV system is well known. Since the gravimetric energy density and the possible storage time of H_2 are superior to battery, capacitance and flywheel [4] [5] [6] [7], H_2 is suitable for long storage and transportation. The combination system of PV and H_2 produced by water electrolyzer using renewable energy sources have been studied numerically as well as experimentally [8]-[23]. Energy and exergy analysis [8] [9] [10], economic assessment [11] [12] [13] [14] [15], environmental assessment [16] [17] and dynamic control procedure in a short time [18] [19] [20] were reported. Though the storage characteristics of H_2 produced by water electrolisys are investigated [21] [22], there are a few reports that investigate the transportation system of H_2 produced by water electrolysis using the power generated by renewable energy sources [3] [23], which are only discussed about CO_2 emission and more investigations are necessary from the viewpoint of energy assessment. In addition, there is no study considering the H_2 produced by water electrolysis using the power generated by large scale photovoltaics.

In this paper, a desktop case study has been conducted on a proposed energy supply chain. The proposed energy supply chain consists of solar panels, water electrolyzer, H_2 liquefaction process (or conversion process from H_2 into organic hydride), transportation by tank truck for land as well as tanker for marine and fuel cell (FC). Photovoltaic power generation of megawatt class is assumed to be installed in Kuala Lumpur, Kolkata, Beijing and Ulan Bator. The power generation characteristics of PV system assumed to be installed in four Asian cities were evaluated using meteorological data of METPV-ASIA [24]. The H_2 is produced by the water elecrolyzer with power generated by PV system. The H_2 is assumed to be transported after liquefaction or conversion into organic hydride. To convey the H_2 energy from each city in Asia to Tokyo in Japan, tank truck and tanker are considered for land and marine transportation, respectively. This study investigates the electricity generated by PV system assumed to be installed in four Asian cities and the amount of H_2 produced by water electrolysis using the electricity generated by PV system. This study also investigates the energy efficiency of the proposed energy supply chain and the amount of CO_2 emission in the transportation process.

2. The Proposed Energy Supply Chains

This study proposes four energy supply chains sourced from four Asian cities to end users in Tokyo Japan, with the following assumptions:

1) Megawatt class of PV array would be installed in Asian cities where solar resources are good, *i.e.*, Kuala Lumpur (Latitude: 3.08˚N, Longitude: 101.42˚E), Kolkata (Latitude: 22.34˚N, Longitude: 88.22˚E), Beijing (Latitude: 39.54˚N, Longitude: 116.23˚E) and Ulan Bator (Latitude: 47.55˚N, Longitude: 106.55˚E). H_2 is produced by water electrolyzer using the electricity generated by PV system.
2) H_2 is liquefied or converted into organic hydride as a carrier.
3) Liquefied H_2 or organic hydride is transported from Asian cities to the nearest seaport by tank truck.
4) Liquefied H_2 or organic hydride is transported from the sea port to Tokyo, Japan by tanker. When transporting liquefied H_2, the transportation loss due to the boil-off rate of tanker is counted for estimation of amount of H_2 after transportation.
5) Liquefied H_2 or organic hydride is vaporized or reconverted into H_2 and H_2 is used for FC system to generate the power, in Japan.

In this study, the process 5 is ignored in the assessment. Figure 1 shows the world map showing the location of each city to be assessed in this study.

Figure 1. Location of the cities involved in this study.

3. Methodology of the Study

3.1. Estimation of Power Generation from the PV System

The electricity generated by PV system is calculated by using the following equation [25]:

$$E_{PV} = H \times K \times P/1 \tag{1}$$

where E_{PV} is hourly electricity generation from the PV system (kWh), H is amount of solar radiation (kWh/m^2), K is power conversion factor (−), P is system's peak capacity of PV (kW$_p$), 1 is solar peak radiation, *i.e.*, 1 kW/m^2. The hourly solar radiation data of the reference [24] are used for calculating the hourly electric power of PV system.

In this study, the high performance PV P250a Plus produced by Panasonic whose module conversion efficiency and maximum power per module are 19.5% and 250 W [26], respectively is adopted for PV system. The size of each PV module is 1580 mm × 812 mm × 35 mm. To calculate K, the performance value of state-of-the-art commercial devise is used. K is calculated by using the following equation [1]:

$$K = K_p \times K_m \times K_i \tag{2}$$

where K_p is power conversion efficiency of power conditioner (−), K_m is correction factor decided by module temperature (−), K_i is power generation loss by interconnecting and dirty of module surface (−). In this study, K_p and K_i are set at 0.945 and 0.95, respectively. K_p is assumed by referring to the performance of commercial power conditioning device VBPC259B3 manufactured by Panasonic [27]. K_m is calculated by the following equation [1]:

$$K_m = 1 - \frac{(T_m - T_s)C}{100} \tag{3}$$

where T_m is PV module temperature (degree Celsius), T_s is temperature under standard test condition (=25 degree Celsius) (degree Celsius), C is temperature correction factor which is 0.35 [28] (%/degree Celsius). The temperature characteristics of PV module which is adopted for this study are referred. T_m is calculated by using the following equation [29]:

$$T_m = T_a + \left(\frac{46}{0.41U_m^{0.8} + 2}\right)H - 2 \tag{4}$$

where T_a is ambient air temperature (degree Celsius), U_m is wind velocity over module of PV (m/s). In this equation, the convection heat transfer by wind around the PV module is considered.

The meteorological data, such as solar radiation, the ambient air temperature, and wind velocity of the four Asian cities were from the data base of METPV-ASIA from 1999 to 2005 [24].

Table 1 and **Figure 2** show monthly and annual mean temperature [30], and monthly precipitation [31] for the four Asian cities, respectively. These data are used for estimation of electricity generated by PV system and discussion later.

Table 1. Monthly and annual mean temperature for four Asian cities (Unit: degree Celsius).

	Kuala Lumpur	Kolkata	Beijing	Ulan Bator
January	26.9	12.6	−3.1	−21.7
February	27.3	23.6	0.2	−16.1
March	27.6	28.0	6.7	−7.0
April	27.7	30.4	14.8	1.8
May	28.0	30.9	20.8	10.0
June	27.9	30.4	24.9	16.0
July	27.5	29.4	26.7	18.5
August	27.4	29.3	25.5	16.0
September	27.2	29.2	20.7	9.5
October	27.1	28.1	13.7	0.9
November	26.8	25.0	5.0	−10.6
December	26.7	21.2	−0.9	−19.0
Annual mean	27.3	26.5	12.9	−0.1

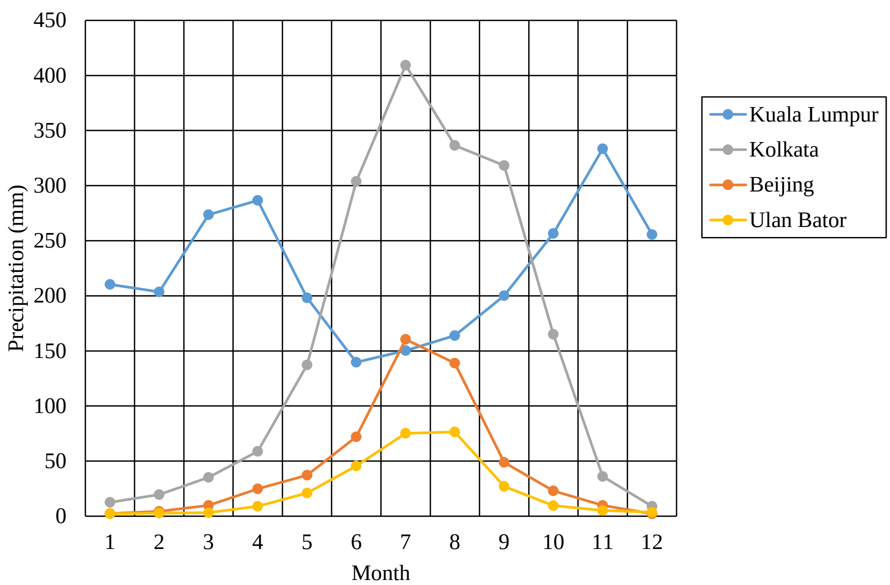

Figure 2. Monthly precipitation for four Asian cities.

3.2. Estimation of H_2 Produced by Water Electolysis

The Type-S electrolyzer manufactured by IHT [32] [33] whose H_2 production rate, power consumption and electrolysis efficiency are 760 Nm^3/h, 4.45 kHW/Nm^3 and 79.5%, is used in this study. The amount of H_2 could be produced by the power generated from PV system is calculated by the following equation [1]:

$$V_{H_2} = \frac{\eta_e E_{PV}}{P_e} \tag{5}$$

where V_{H2} is amount of H_2 produced (Nm^3), P_e is power consumption (kWh/Nm^3), η_e is electrolysis efficiency (–). In this study, it is assumed that the electrolyzer can be operated following the power generation characteristics of PV system every time and the produced H_2 can be stored as well as used instantaneously.

It is assumed that the H_2 produced by electolyzer would be used to generate power through a polymer electrolyte fuel cell (PEFC) system. H_2 is converted into electricity by FC following the below equation [1]:

$$H_2 + 1/2O_2 = H_2O + \eta_f Q \tag{6}$$

where η_f is power generation efficiency of latest PEFC stationary system based on lower heating value (=0.39) [34], Q is lower heating value of H_2 (=242) (kJ/mol). It is assumed that the energy loss for operating pump to preserve and provide gases is ignored.

3.3. Evaluation of Transportation Process

It is necessary that the H_2 produced by water electrolysis using the power generated by PV system is converted into a transportable media before shipped to Japan, due to low energy density of H_2 in gas form. In this study, liquefaction and conversion of H_2 into organic hydride are considered as the transportable media of H_2.

In the case of liquefied H_2 transportation, the volume of H_2 is changed by 1/800 by means of liquefaction [35]. Since the energy efficiency of liquefaction of H_2 is 73.6% [36], the energy consumption of liquefaction is estimated by the energy efficiency and the amount of H_2 to be liquefied. The volume of tank truck is 23 m^3 [37] and the volume of tanker is 2500 m^3 [38], which are leading-edge types. The fuel for tank truck is light oil and the fuel efficiency is 2.34 km/L [39]. The fuel for tanker is heavy oil and the fuel efficiency is 0.87 km/L [40]. The speed of the tanker is 36.1 km/h [41] and the boil-off rate is 0.4%/day [38], which is used for counting H_2 loss in marine transportation. The lower heating value of light oil and heavy oil are 35.5 MJ/L [42] and 46.4 MJ/L [43], respectively. The CO_2 emission coefficient of light oil and heavy oil are 2.62 kg-CO_2/L [44] and 3.41 kg-CO_2/L [43], respectively. For land transportation, it is assumed to transport from the each city to the nearest sea port, then to Tokyo port in Japan through marine transportation by the tanker. The energy consumption of transportation as well as the amount of CO_2 emission in the transportation process is estimated using the distance between each city and the nearest sea port as well as the sea port and Tokyo port in Japan.

In the case of organic hydride transportation, H_2 can be transported by the volume of 1/500 compared to the gases H_2 at atmospheric pressure [35]. This study considers the reaction of C_7H_8 and H_2 into C_7H_{14} as the conversion process of organic hydride. Since the enthalpy loss of C_7H_{14} for emitting H_2, *i.e.*, the necessary energy for emitting H_2 which is an endothermic reaction is 67.5 kJ/mol-H_2 [45]; the energy consumption of conversion process of organic hydride is estimated by the enthalpy loss and the amount of H_2. In this study, the energy consumption of absorbing H_2 is neglected since absorbing H_2 by C_7H_8 is an exothermic reaction. Since the organic hydride can be transported by general tank truck and tanker for petroleum oil [46], this study assumes the volume of tank truck and tanker are 20 m^3 [47] for land transportation and 20000 m^3 [48] for marine transportation, respectively. The fuel for tank truck is light oil and the fuel efficiency is 2.34 km/L [39]. The fuel for tanker is heavy oil and the fuel efficiency is 0.87 km/L [40].

4. Results and Discussion

4.1. Assessment on Characteristics of Large Scale PV System Assumed to be Installed in Four Cities

At first, the optimum tilt angle and orientation angle to install solar panel for each city is investigated using the hourly meteorological data base [24] for the four Asian cities. The monthly and annual solar radiation are estimated summing the hourly data in order to decide the annual optimum tilt angle and orientation angle for power generation of PV system. After that, the power generation characteristics of PV system under the optimum tilt angle and orientation angle condition are investigated.

As an example, **Figure 3** shows the relationship between tilt angle and amount of solar radiation for different orientation angles in the case of Kuala Lumpurin January. As to orientation angle, 0 degree means south and the angle increases by 30 degree in a clockwise fashion. **Table 2** lists the annual amount of solar radiation for different tilt angles and orientation angles in the case of Kuala Lumpur. From this table, it is seen that the highest amount of solar radiation is obtained at tilt angle of 20 degree and orientation angle of 270 degree (*i.e.* east). **Table 3** lists the annual amount of solar radiation for different tilt angles and orientation angles in the case of Kolkata. From this table, it is seen that the highest amount of solar radiation is obtained at tilt angle of 30 degree and orientation

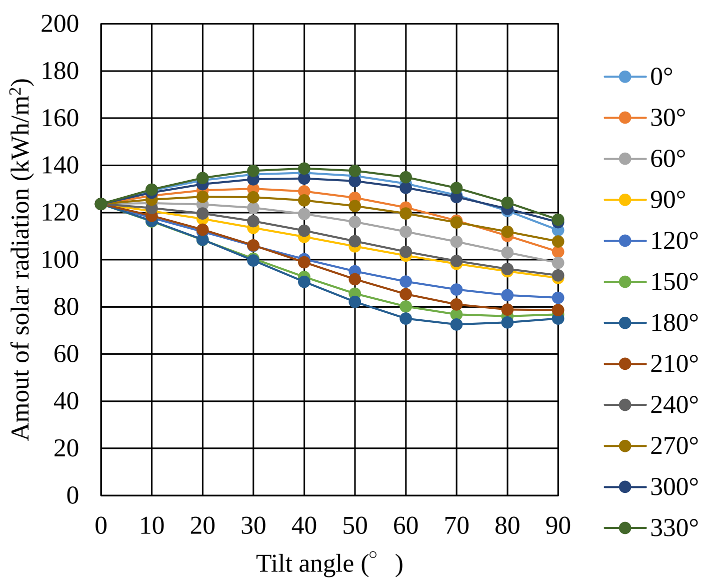

Figure 3. Relationship between tilt angle and amount of solar radiation for different orientation angles (Kuala Lumpur, January).

Table 2. Annual amount of solar radiation for different tilt angles and orientation angles in the case of Kuala Lumpur (Unit: kWh/m^2).

	0˚	30˚	60˚	90˚	120˚	150˚	180˚	210˚	240˚	270˚	300˚	330˚
0˚	1562	1562	1562	1562	1562	1562	1562	1562	1562	1562	1562	1562
10˚	1557	1545	1538	1534	1534	1540	1550	1563	1574	1579	1577	1569
20˚	1537	1517	1506	1501	1501	1506	1524	1550	1575	1588	1582	1562
30˚	1498	1475	1467	1464	1458	1459	1480	1520	1561	1583	1573	1538
40˚	1444	1420	1421	1422	1411	1401	1420	1474	1535	1565	1550	1498
50˚	1375	1356	1370	1376	1360	1335	1348	1416	1497	1537	1515	1445
60˚	1299	1288	1319	1332	1309	1268	1270	1351	1451	1499	1471	1383
70˚	1221	1222	1269	1290	1261	1204	1197	1285	1401	1454	1421	1317
80˚	1159	1163	1224	1249	1218	1151	1136	1224	1350	1407	1368	1254
90˚	1110	1118	1186	1214	1183	1112	1091	1174	1301	1358	1317	1199

Table 3. Annual amount of solar radiation for different tilt angles and orientation angles in the case of Kolkata (Unit: kWh/m^2).

	0˚	30˚	60˚	90˚	120˚	150˚	180˚	210˚	240˚	270˚	300˚	330˚
0˚	1582	1582	1582	1582	1582	1582	1582	1582	1582	1582	1582	1582
10˚	1642	1630	1604	1570	1536	1511	1504	1518	1548	1583	1615	1637
20˚	1686	1665	1619	1555	1486	1432	1416	1446	1509	1580	1639	1677
30˚	1706	1679	1619	1532	1430	1344	1315	1366	1463	1566	1647	1695
40˚	1702	1672	1605	1502	1373	1254	1212	1283	1413	1543	1637	1690
50˚	1673	1643	1576	1466	1317	1171	1120	1204	1363	1513	1614	1663
60˚	1621	1596	1537	1426	1268	1104	1050	1139	1317	1476	1576	1617
70˚	1549	1533	1488	1385	1227	1057	1001	1092	1276	1436	1527	1552
80˚	1462	1459	1433	1345	1194	1030	974	1065	1241	1392	1470	1475
90˚	1370	1380	1377	1305	1171	1024	969	1054	1213	1348	1409	1393

angle of 0 degree (*i.e.* south). Table 4 lists the annual amount of solar radiation for different tilt angles and orientation angles in the case of Beijing. From this table, it is seen that the highest amount of solar radiation is obtained at tilt angle of 50 degree and orientation angle of 0 degree (*i.e.* south). Table 5 lists the annual amount of solar radiation for different tilt angles and orientation angles in the case of Ulan Bator. From this table, it is seen that the highest amount of solar radiation is obtained at tilt angle of 60 degree and orientation angle of 0 degree (*i.e.* south).

According to Tables 2-5, the optimum tilt angel increases with increasing latitude. In addition, the optimum orientation angle is 0 degree except Kuala Lumpur. Kuala Lumpur is located near the equator and the solar altitude is the highest on the spring equinox day and the autumnal equinox day, which are different from the other cities. Therefore, the optimum orientation angle for Kuala Lumpur would be different compared to the other cities. The power of PV system is estimated under the condition installing solar panel at this optimum tilt angle and orientation angle.

Figure 4 shows the monthly electricity generated by the PV system in the four

Table 4. Annual amount of solar radiation for different tilt angles and orientation angles in the case of Beijing (Unit: kWh/m²).

	0˚	30˚	60˚	90˚	120˚	150˚	180˚	210˚	240˚	270˚	300˚	330˚
0˚	1389	1389	1389	1389	1389	1389	1389	1389	1389	1389	1389	1389
10˚	1496	1478	1436	1379	1322	1280	1268	1289	1337	1396	1450	1486
20˚	1589	1557	1482	1377	1264	1174	1145	1191	1291	1407	1508	1573
30˚	1658	1616	1516	1374	1212	1074	1029	1098	1248	1414	1551	1636
40˚	1700	1650	1536	1368	1168	989	937	1019	1211	1415	1578	1677
50˚	1712	1661	1541	1358	1134	927	865	960	1182	1409	1585	1690
60˚	1697	1647	1528	1343	1109	889	817	923	1159	1396	1577	1677
70˚	1654	1609	1502	1322	1092	876	795	909	1143	1376	1548	1639
80˚	1585	1550	1460	1296	1080	880	803	910	1129	1350	1505	1578
90˚	1494	1472	1406	1264	1071	895	829	922	1118	1316	1448	1497

Table 5. Annual amount of solar radiation for different tilt angles and orientation angles in the case of Ulan Bator (Unit: kWh/m²).

	0˚	30˚	60˚	90˚	120˚	150˚	180˚	210˚	240˚	270˚	300˚	330˚
0˚	1329	1329	1329	1329	1329	1329	1329	1329	1329	1329	1329	1329
10˚	1467	1458	1412	1343	1267	1207	1177	1189	1239	1310	1382	1440
20˚	1592	1575	1490	1359	1211	1089	1031	1061	1163	1300	1436	1542
30˚	1691	1667	1550	1367	1158	983	910	952	1099	1291	1477	1620
40˚	1760	1732	1591	1368	1113	899	814	868	1050	1280	1502	1674
50˚	1796	1766	1609	1364	1080	839	746	810	1016	1268	1510	1699
60˚	1799	1771	1609	1354	1061	812	706	783	994	1251	1501	1697
70˚	1769	1744	1585	1336	1050	811	704	782	982	1230	1475	1666
80˚	1707	1688	1546	1312	1045	826	732	796	976	1203	1432	1610
90˚	1616	1606	1488	1280	1041	847	767	818	973	1176	1375	1530

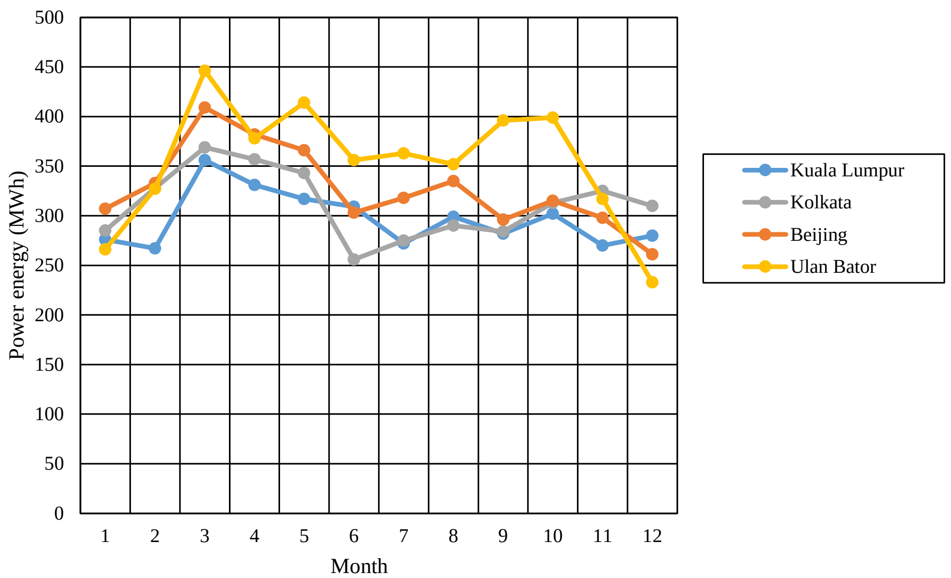

Figure 4. Monthly electricity generated by PV system for four Asian cities.

cities. In this estimation, it was assumed that the PV system consists of 10,000 solar panels (=2.5 MW; one panel = 0.25 kW). The annual electricity generated by the PV system for Kuala Lumpur, Kolkata, Beijing and Ulan Bator are 3.56 GWh, 3.74 GWh, 3.92 GWh and 4.25 GWh, respectively.

According to Figure 4, it is seen that with the same solar PV panels, the PV system in Ulan Bator could be generated the largest amount of annual power output due to its lower annual mean ambient temperature and precipitation. On the other hand, in the case of Kuala Lumpur, the annual mean temperature and annual precipitation are the highest among the four cities, thus generating the smallest annual power output. In addition, it is revealed from Figure 4 that the monthly electricity generated by the PV system is the highest in March irrespective of city.

4.2. Assessment on H_2 Production by Water Electrolysis and Transportation by Liquefied H_2 from Each City to Tokyo

Table 6 lists the monthly amount of produced H_2 by water electrolysis using the electricity generated by PV system consisting of 10,000 PV panels or modules having total peak capacity of 2.5 MW, assumed to be installed in four cities. The annual amount of H_2 produced by water elerctrolys is using the electricity generated by the PV system installed in Kuala Lumpur, Kolkata, Beijing and Ulan Bator are 28.4 Mmol, 29.8 Mmol, 31.3 Mmol and 33.9 Mmol, respectively.

Table 6 also lists the decreased volume of liquefied H_2 by boil-off rate. It increases with increasing marine transportation distance and total amount of liquefied H_2.

According to Table 6, the largest amount of produced H_2could be delivered to Tokyo is obtained in the case of Ulan Bator, while the smallest amount is obtained in the case of Kuala Lumpur. These results follow the characteristics of electricity generated by the PV system shown in Figure 3.

Table 7 lists the annual amount of produced H_2, the volume of liquefied H_2,

Table 6. Monthly amount of produced H_2 and delivered in Tokyo from four Asian cities.

	Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Kuala Lumpur	Amount of produced H_2 (Mmol)	2.21	2.13	2.84	2.64	2.52	2.46	2.17	2.39	2.25	2.41	2.16	2.23	28.4
	Decreased volume of liquefied H_2 by boil-off rate (m^3/year)													22.3
Kolkata	Amount of produced H_2 (Mmol)	2.27	2.61	2.94	2.84	2.74	2.05	2.20	2.32	2.27	2.49	2.59	2.47	29.8
	Decreased volume of liquefied H_2 by boil-off rate (m^3/year)													33.4
Beijing	Amount of produced H_2 (Mmol)	2.45	2.66	3.27	3.05	2.92	2.42	2.54	2.67	2.36	2.51	2.37	2.08	31.3
	Decreased volume of liquefied H_2 by boil-off rate (m^3/year)													14.0
Ulan Bator	Amount of produced H_2 (Mmol)	2.13	2.61	3.56	3.02	3.30	2.84	2.90	2.81	3.16	3.18	2.53	1.86	33.9
	Decreased volume of liquefied H_2 by boil-off rate (m^3/year)													15.2

Table 7. Transportation and conversion characteristics from four Asian cities (H_2 liquefaction).

	Kuala Lumpur	Kolkata	Beijing	Ulan Bator
Annual amount of produced H_2 (Nm^3/year)	6.362×10^5	6.673×10^5	7.011×10^5	7.591×10^5
Volume of liquefied H_2 (m^3/year)	795.2	834.1	876.4	948.9
Number of tank truck (−)	35	37	39	42
Amount of CO_2 emission for all tank truck (kg-CO_2)	2.35×10^3	3.73×10^3	7.42×10^3	7.05×10^5
Energy consumption for all tank truck (GJ)	31.9	50.5	100.6	9557.7
Number of tanker (−)	0.319	0.334	0.351	0.380
Amount of CO_2 emission for a tanker (kg-CO_2)	2.05×10^4	2.95×10^4	1.04×10^4	1.04×10^4
Energy consumption for a tanker (GJ)	277.9	400.4	141.3	141.3
Energy consumption in all transportation process (GJ)	310	451	242	9699
Amount of CO_2 emission in all transportation process (kg-CO_2)	2.3×10^4	3.3×10^4	1.8×10^4	71.6×10^4
Energy consumption for liquefaction (GJ)	1764	1827	1968	2131
Total energy consumption (GJ)	2.07×10^3	2.28×10^3	2.21×10^3	11.83×10^3
Electricity generated by FC in Tokyo (after transportation) (GWh)	0.722	0.750	0.807	0.874
Ratio of total energy consumption to calorific value of H_2 delivered to Tokyo (−)	0.310	0.329	0.296	1.466

Table 8. The nearest port, land transportation distance, marine transportation distance and marine transportation days for four Asian cities.

	Kuala Lumpur	Kolkata	Beijing	Ulan Bator
The nearest port	Port Klang	Haldia	Tianjin	Tianjin
Land transportation distance (km)	60	90	170	15,000
Marine transportation distance (km)	5900	8500	3000	3000
Marine transportation days	7	10	4	4

the number of tank truck transporting for all liquefied H_2, the amount of CO_2 emission for all tank truck and the energy consumption for all tank truck for four Asian cities. In addition, Table 7 also lists the number of tanker transporting for all liquefied H_2, the amount of CO_2 emission for a tanker, the energy consumption for a tanker, the energy consumption in all transportation process, the amount of CO_2 emission in all transportation process, the energy consumption for liquefaction, the electricity generated by FC in Tokyo (after transportation), the total energy consumption and the ratio of total energy consumption to calorific value of H_2 delivered in Tokyo for four Asian cities. In this estimation, the 2.5 MW PV system was assumed to be installed in the source cities.

According to Table 7, it is revealed that the largest amount of CO_2 emission and energy consumption for all tank truck are obtained in the case of Ulan Bator, while the smallest amount of CO_2 emission and energy consumption for all tank truck are obtained in the case of Kuala Lumpur. Since the distance from Ulan Bator to the nearest seaport is very long according to Table 8 [49] and more number of tank truck is needed compared to the other cities, the amount of CO_2 emission and energy consumption for all tank truck are larger in the case of Ulan Bator. On the other hand, the distance from Kuala Lumpur to the nearest seaport is the shortest and the number of tank truck is also the fewest among four cities, resulting that the amount of CO_2 emission and energy consumption for all tank truck are smaller in the case of Kuala Lumpur.

As to marine transportation, it is revealed that the largest amount of CO_2 emission and energy consumption for a tanker are obtained in the case of Kolkata, while the smallest amount of CO_2 emission and energy consumption for a tanker are obtained in the case of Beijing and Kuala Lumpur. In this study, the amount of CO_2 emission and energy consumption for a tanker depend on marine transportation distance only. Since the marine transportation distance in the case of Kolkata is the longest and those in the case of Beijing and Kuala Lumpur are the shortest among four cities, the above mentioned characteristics on marine transportation are lead.

As to all transportation process, it is revealed that the largest amount of CO_2 emission and energy consumption are obtained in the case of Ulan Bator since the impact of land transportation is significant. On the other hand, it is seen that the smallest amount of CO_2 emission and energy consumption are obtained in the case of Beijing. Though the impact of land transportation is not small in the case of Beijing, it is believed that this result is obtained by smaller impact of the marine transportation compared to the other cities.

It is known that the electricity generated by the FC system is about 20% of that by the PV system under the assumption of this study. Since the amount of energy is decreased by energy conversion, it is important to transport the large amount of H_2 for fulfilling the energy demand of remote country.

Table 7 reveals that the total energy consumption during the transportation and the ratio of total energy consumption to calorific value of H_2delivered are the largest in the case of Ulan Bator, while they are the smallest in the case of Beijing. In the case of Ulan Bator, the ratio is even greater than 1 which means it would cost more energy to transport H_2 than energy (contained in H_2) delivered. Table 7 implies Beijing is the best energy effective case.

4.3. Assessment on H_2 Production by Water Electrolysis and Transportation by Organic Hydride from Each City to Tokyo

Table 9 lists the annual amount of produced H_2, the volume of organic hydride, the number of tank truck transporting for all organic hydride, the amount of CO_2 emission for all tank truck and the energy consumption for all tank truck for four Asian cities. In addition, Table 9 also lists the number of tanker transporting for all organic hydride, the amount of CO_2 emission for a tanker, the energy consumption for a tanker, the energy consumption in all transportation process, the amount of CO_2 emission in all transportation process, the energy consumption for liquefaction, the electricity generated by FC in Tokyo (after transportation), the total energy consumption and the ratio of total energy consumption to calorific value of H_2 after transportation for four Asian cities. In this estimation, the monthly amount of produced H_2 by water electrolysis using the

Table 9. Transportation and conversion characteristics for four Asian cities (organic hydride).

	Kuala Lumpur	Kolkata	Beijing	Ulan Bator
Annual amount of produced H_2 (Nm^3/year)	6.362×10^5	6.673×10^5	7.011×10^5	7.591×10^5
Volume of organic hydride (m^3/year)	1272.3	1334.6	1402.2	1518.3
Number of tank truck (−)	64	67	71	76
Amount of CO_2 emission for all tank truck (kg-CO_2)	4.30×10^3	6.75×10^3	13.51×10^3	12.76×10^5
Energy consumption for all tank truck (GJ)	58.3	91.5	183.1	172.9×10^2
Number of tanker (−)	0.0637	0.0688	0.0702	0.0760
Amount of CO_2 emission for a tanker (kg-CO_2)	2.05×10^4	2.95×10^4	1.04×10^4	1.04×10^4
Energy consumption for a tanker (GJ)	277.9	400.4	141.3	141.3
Energy consumption in all transportation process (GJ)	336	492	324	174.4×10^2
Amount of CO_2 emission in all transportation process (kg-CO_2)	2.5×10^4	3.6×10^4	2.4×10^4	128.6×10^4
Energy consumption for conversion of organic hydride (GJ)	1917	2011	2113	2288
Total energy consumption (GJ)	2.25×10^3	2.50×10^3	2.44×10^3	19.73×10^3
Electricity generated by FC in Tokyo (after transportation) (GWh)	0.743	0.781	0.820	0.888
Ratio of total energy consumption to calorific value of H_2 delivered to Tokyo (−)	0.328	0.347	0.322	2.405

electricity generated by the PV system consisting of 10,000 PV panels or modules having total peak capacity of 2.5 MW as shown in Table 6 is used.

According to Table 9, it is revealed that the largest amount of CO_2 emission and energy consumption for all tank truck are obtained in the case of Ulan Bator, while the smallest amount of CO_2 emission and energy consumption for all tank truck are obtained in the case of Kuala Lumpur, which is the same tendency as H_2 liquefaction case. Since the distance from Ulan Bator to the nearest sea port is very long according to Table 8 [49] and more number of tank truck is needed compared to the other cities, the amount of CO_2 emission and energy consumption for all tank truck are larger in the case of Ulan Bator. On the other hand, the distance from Kuala Lumpur to the nearest sea port is the shortest and the number of tank truck is also the fewest among four cities, resulting that the amount of CO_2 emission and energy consumption for all tank truck are smaller in the case of Kuala Lumpur.

As to marine transportation, it is revealed that the largest amount of CO_2 emission and energy consumption for a tanker are obtained in the case of Kolkata, while the smallest amount of CO_2 emission and energy consumption for a tanker are obtained in the case of Beijing and Kuala Lumpur, which can be explained by the same discussion as H_2 liquefaction case. In this study, the amount of CO_2 emission and energy consumption for a tanker depend on marine transportation distance only. Since the marine transportation distance in the case of Kolkata is the longest and that in the case of Beijing and Kuala Lumpur is the shortest among four cities, the above mentioned characteristics on marine transportation are obtained.

As to all transportation process, it is revealed that the largest amount of CO_2 emission and energy consumption are obtained in the case of Ulan Bator, while it is seen that the smallest amount of CO_2 emission and energy consumption are obtained in the case of Beijing, which can be explained by the same discussion as H_2 liquefaction case.

After delivered in Tokyo by organic hydride, the electricity generated by FC system is about 21% of that by the PV system under the assumption of this study.

Table 9 reveals that the total energy consumption and the ratio of total energy consumption to calorific value of H_2 delivered are the largest in the case of Ulan Bator, while those are the smallest in the case of Beijing, which is the same tendency as H_2 liquefaction case. Since the annual amount of produced H_2 in the case of Beijing is the largest compared to the other cities except Ulan Bator and the energy consumption in all transportation process is the smallest among four cities, Beijing is the best energy effective case.

Comparing the ratio of total energy consumption to calorific value of H_2 delivered between H_2 liquefaction case and organic hydride case, the ratio in the case of H_2 liquefaction is smaller than that in the case of organic hydride. When converting gases H_2 into liquefied H_2 or organic hydride, the volume ratios of H_2 liquefaction and conversion into organic hydride are 1/800 and 1/500, respectively. Therefore, the converted volume after H_2 liquefaction is smaller than that after conversion into organic hydride. In addition, the volume of tank truck for liquefied H_2 is larger than that for organic hydride, resulting that the number of tank truck for land transportation of liquefied H_2 is smaller. Consequently, the ratio of total energy consumption to calorific value of H_2 after transportation in the case of H_2 liquefaction is smaller than that in the case of organic hydride due to impact of land transportation.

From the investigation of this study, it is revealed that the proposed energy supply chain is the optimum in the case of Beijing. On the other hand, the introduction of proposed energy supply chain is not effective in the case of Ulan Bator due to very long land transportation distance.

5. Conclusions

This study proposed an energy supply chain which consists of solar panels, water electrolyzer, H_2 liquefaction process (or conversion process from H_2 into organic hydride), transportation by tank truck for land as well as tanker for marine and FC. This study investigated the electricity generated by PV system assumed to be installed in four Asian cities using the meteorological data and the amount of H_2 produced by water electrolysis using the electricity generated by PV system. This study also investigated the energy efficiency of the proposed energy supply chain and the amount of CO_2 emission in the transportation process. As a result, the following conclusions have been drawn:

1) The largest amount of electricity generated from the same size PV systems is obtained in the case of Ulan Bator, while the smallest amount of electricity

generated by the PV system is obtained in the case of Kuala Lumpur. The monthly electricity generated by the PV system is the highest in March irrespective of city investigated.

2) When assuming 2.5 MW PV panel installed in four cities in the case of H_2 liquefaction, the annual electricity could be generated by the FC system in Tokyo is 0.722 GWh, 0.750 GWh, 0.807 GWh and 0.874 GWh, in the cases of Kuala Lumpur, Kolkata, Beijing and Ulan Bator, respectively. The electricity generated by the FC system in Tokyo is about 20% of the electricity generated by the PV system in the source cities. On the other hand, in the case of organic hydride, the annual electricity could be generated by the FC system in Tokyo is 0.743 GWh, 0.781 GWh, 0.820 GWh and 0.888 GWh, in the cases of Kuala Lumpur, Kolkata, Beijing and Ulan Bator, respectively. The electricity generated by the FC system is about 21% of that by PV system in source cities.
3) As expected the CO_2 emission from the transportation from Ulan Batorto, Tokyo is the largest among that from four cities due to long land transportation distance.
4) Comparing the ratio of total energy consumption to calorific value of H_2 delivered between H_2 liquefaction case and organic hydride case, the ratio of total energy consumption to calorific value of H_2 delivered in the case of H_2 liquefaction is generally smaller than that in the case of organic hydride.
5) The proposed energy supply chain from Beijing to Tokyo is the optimum, while the chain from Ulan Bator to Tokyo is not energy effective at all due to very long land transportation distance.

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