Life Cycle Assessment of CO_2 emission from Multigeneration of Water-Electricity-Ammonia Scheme using Sunlight in arid/semi-arid region and Seawater through Pipeline

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Abstract
Water, electricity, and ammonia (artificial fertilizer) are essential for human welfare. The self-sufficient and sustainable productions of them from renewable resources are indispensable for social security and the future society. In this study, we proposed the Water-Electricity-Ammonia (WEA) scheme that produces electricity, freshwater, and ammonia and supplies them at a certain ratio. We investigated the life cycle CO_2 ($LCCO_2$) emission from the case of inland cities in arid/semi-arid regions that obtain the three products (electricity, water, and ammonia) generated by photovoltaic (PV) and seawater obtained through a pipeline connecting the ocean and the cities. This study unraveled the necessary condition to reduce $LCCO_2$ emission: the allocation ratio of PV electricity for the three productions and the geographical conditions of inland cities. To reduce $LCCO_2$ emission, allocating PV power to seawater desalination is suitable if the city is in a lowland area, and ammonia synthesis is preferable if the city is in a highland area. Note that the WEA scheme applied to most inland cities, even in extreme geographical conditions, reduces $LCCO_2$ emissions compared to conventional production methods by optimizing the PV allocation of electricity, freshwater, and ammonia production.

1. Introduction

Water, energy, and food (WEF) are essential for human welfare, and the sustainable supplies of WEF are the targets of the sustainable development goals (SDGs). Continuous pressure on these resources from a rapidly increasing population, coupled with expectations of high standards of living, presents a challenge for future generations. Although the strong dependence on other countries for these imports should be avoided for social security, few countries are self-sufficient in all WEF. It is vital to increase the self-sufficiency rate. Moreover, renewable resources should be employed for a sustainable future.

In modern societies, energy (especially electricity) resource has mainly been fossil fuels. Fossil resources are unevenly distributed, making it difficult for all regions to be self-sufficient. Meanwhile, photovoltaic (PV) is getting inexpensive and serves electricity at a low cost for many areas.[1] Moreover, PV less interferes with water and food supply than other renewable energy sources such as biomass.[2] Solar power is available in many regions, and thus energy self-sufficiency is becoming feasible. Of course, PV is a renewable energy source and is suitable for the sustainable future

As for water supply, it is not simple to satisfy water demand in arid/semi-arid regions. In addition to the original scarcity of water in these areas, a rapidly increasing population and climate change make the water supply further difficult.[3] Freshwater withdrawal from surface water and groundwater often causes problems such as seasonal shortage, ground subsidence, and environmental degradation. To avoid these issues and meet the demand, seawater is appropriate as a renewable water resource because of its abundance.[4] However, while it is relatively easy for coastal areas to be supplied the desalinated water, it is much more difficult for inland areas where access to seawater is hard. On the other hand, as a very recent example, the Jordan government launched the National Water Carrier Project, which will construct a pipeline, desalinate seawater, and deliver it inland via about 200 km pipeline for the agricultural and water sectors by 2027 at the cost of USD 2.5 billion.[5,6] Furthermore, there are many projects to convey freshwater via pipeline, such as the Goldfields Water Supply Scheme with the 556 km pipeline,[7] and GMR (Great Man-Made River) Water Supply Project with more than 2400 km pipeline,[8] although these are not examples of desalination. Thus, it is practical to supply water to far inland areas through pipelines. It is also possible even for inland cities to supply water self-sufficiently from a renewable source, seawater, and solar power required for the energy in desalination.

Crop production to meet the increasing food demand requires irrigation water and artificial fertilizers to enlarge the arable land area and promote unit yield. If the water supply is sufficient, irrigation water can be provided, and, notably, artificial nitrogen fertilizer can be self-sufficient and renewable through ammonia synthesis. Ammonia can be synthesized from hydrogen obtained from water electrolysis and nitrogen in the air separated from the other gases through cryogenic separation or pressure swing adsorption. Ammonia is an indispensable starting material for artificial nitrogen fertilizers and is essential for crops to improve yields. In current industries, ammonia is synthesized from fossil fuels. Then, "green ammonia," synthesized based on renewable energy, is inevitable for a sustainable future. Obviously, nitrogen in the air is versatile, and thus ammonia can also be self-sufficient and renewable if energy and water are so. Furthermore, ammonia is attracting attention as an energy carrier. It liquefies at room temperature at approximately 1 MPa, and has a high energy density in terms of weight and volume, making it suitable for storage and transportation of renewable energy.[9] Ammonia-fueled power generation technology is being established.[10] Therefore, ammonia has the potential to replace expensive batteries and have a positive effect on energy use.

Here, we propose the water-electricity-ammonia (WEA) scheme as one of the sustainable systems to self-sufficiently supply water, electricity, and ammonia from a renewable source. The WEA scheme is composed of the following three principles: electricity is generated by renewable energy; desalination and water transportation inland are carried out by the electricity; ammonia is synthesized using nitrogen in the air and hydrogen evolved by water electrolysis using the transported water and the generated electricity. The electricity and water have to be allocated to these three products appropriately depending on the needs. In recent years, WEF "nexus" approach has received global recognition for the interdependencies between water, energy, and food.[11-13] We propose this WEA scheme to settle the demands from the WEF sectors by producing the three products from renewable sources.

The main nexus approach is to optimize the limited resources to satisfy the demand in WEF sectors. To give an overview of researches on nexus, we look at research papers and review articles on a database, the Web of Science (WOS). With the keyword "nexus & water & energy & food," the total number of publications is 1,895 (as of April 8th, 2022). When we searched documents with the criteria "nexus & water & renewable energy & food," the number was 185 (9.7%). With the search term, "nexus & water & energy & food & desalination" and "nexus & water & renewable energy & food & desalination," only 59 (3.1%) and 12 (0.6%) documents are picked up from the WOS, respectively. Previous researches have focused on desalination only in the coastal and dry areas. Desalination is not the mainstream in the WEF nexus. Although many researchers investigated desalination with the distribution via pipelines, very limited literature focuses on the use of renewable energy for these operations.[14-18] For a self-sufficient and sustainable water supply, renewable energy plays a significantly important role. Furthermore, green ammonia originally included productions of freshwater and electricity based on renewable energy. Several researchers have analyzed their economics and energy efficiency,[19-26] but they do not consider supplying freshwater and electricity to other sectors. In the retrieved literature, none have evaluated the supply of water desalinated by renewable energy and green ammonia to inland cities in the context of nexus, which considers the supply to multi sectors with optimization. Since water, electricity, and ammonia are indispensable for human welfare, the WEA scheme to provide them is essential for the future and is a critical subject for a nexus analysis.

In addition, the WEA scheme can combine the three supplies, which enables compensation of negative effects from any supply like the idea of cap-and-trade. For example, if a water supply increases greenhouse gas (GHG) emissions, but an electricity supply sector reduces GHG emissions, the overall GHG emissions can decrease. Eventually, we present the WEA scheme that self-sufficiently supplies renewable resources in combination and can be evaluated based on total outputs.

The advantages of the WEA scheme should be assessed from several points of view, including the environmental impact, economic, security, and resilience. In practice, large-scale power storage is required for steady-state use of PV, and batteries are generally expensive. In other words, it is not yet realistic to entirely rely on electricity from renewable energy for 100% so far. In addition, infrastructure manufacturing is accompanied by CO_2 emissions. Therefore, it is necessary to consider life cycle CO_2 emissions ($LCCO_2$), and it will be essential to establish a method to evaluate $LCCO_2$.

In this study, we examined $LCCO_2$, one of the representative indexes of environmental impact, as a starting point for analyzing the WEA scheme. The CO_2 amount from transport construction/operation depends on the geographical condition of the supply destination, such as distance from the sea and the elevation. Thus, $LCCO_2$ is a function of geographical constraints. Since inventory data, which are functions of these factors, have not been available, this study provided them first and examined $LCCO_2$ with that data set. For the analysis, we chose arid/semi-arid regions where PV costs have dramatically dropped in recent years[27] and where the demand for water and food is high, meaning the needs for WEF are large. We assumed that the desalination plant is constructed near the sea to dispose of concentrated seawater, and the ammonia synthesis plant is allocated near an inland city due to labor. The results showed that supplying PV power as electricity reduces $LCCO_2$ the most. Using PV electricity, desalination reduces $LCCO_2$ when cities are at lower elevations, and ammonia synthesis reduces $LCCO_2$ when cities are at higher elevations. Besides, there are some cases in which desalination or ammonia synthesis increases $LCCO_2$ depending on height. Finally, we report the geographical conditions and the ratio of the PV power allocation to water, electricity, and ammonia production that do not increase $LCCO_2$.

2. Method

2.1 Whole picture of WEA scheme in this analysis

The WEA scheme has several patterns, such as employing concentrated solar power (CSP) for electricity generation, multi-effect distillation (MED) for desalination, etc. The pattern of the WEA scheme analyzed in this study is as follows (the whole picture is in Fig. 1). PV is assumed as an electricity generation method, inexpensive at a large scale in arid/semi-arid regions recently.[27] The PV electricity is used to desalinate seawater via reverse osmosis (RO), the most energy-efficient way currently. The desalinated water is then used to produce hydrogen via water electrolysis using PV electricity. The alkaline water electrolysis is employed, commercially available, and suitable for large-scale production. Nitrogen is separated from the air using the cryogenic separation method, appropriate for large scale. The obtained hydrogen and nitrogen are used to synthesize ammonia by the Haber-Bosch process, which is also commercialized and ideal for large-scale production.

The ammonia synthesis plant is allocated near an inland city due to labor. The synthesis plant includes a water electrolysis plant and a nitrogen cryogenic separation plant. Brine water discharged from RO is generally returned to the sea. As an assumption in this study, a desalination plant is constructed near the sea to return the concentrated seawater to the sea on-site, conveying freshwater to the city via pipeline. In other words, the construction of pipelines necessary to dispose of the concentrated seawater to the sea was omitted. Since this assumption requires a transmission line connecting the seaside desalination plant to the city, the construction and transmission losses of the grid were also included for the estimation of $LCCO_2$ emission. Fig. 2 shows the overall picture of the system boundary conducted in this study.

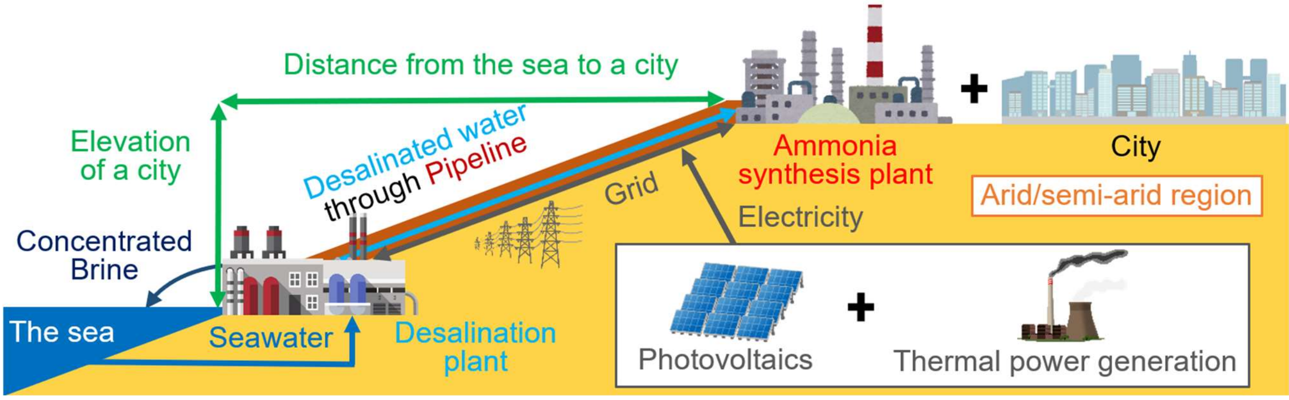

Fig. 1 Conceptual picture of the WEA scheme including the pipeline and the grid to transport water and electricity, respectively.

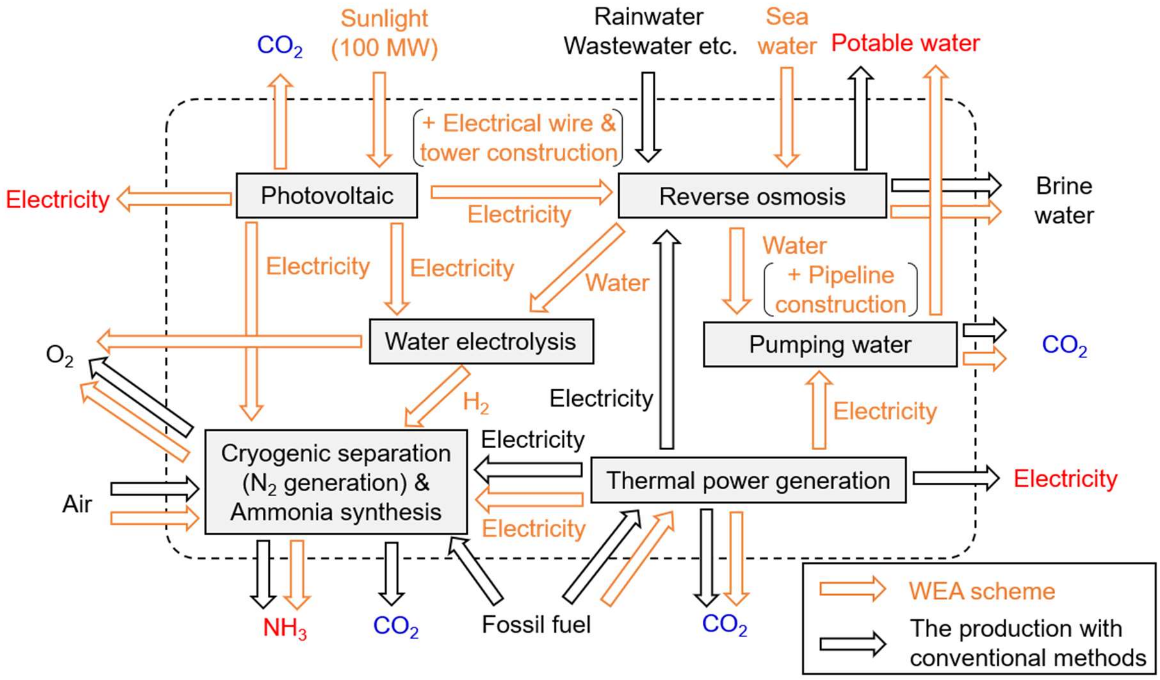

Fig. 2 System boundary of the analyzed WEA scheme

2.2 CO_2 emission from each production process in the WEA scheme

The PV scale (PV_{scale}) is assumed to be sizeable, 100 MWp, since the target is an arid/semi-arid area and is suitable for PV at a large scale. The long-term average of a potential PV electricity generation (PV_{out}) was 4.5 kWh/kWp/day.[28] Thus, the rate of PV operation (PV_{rate}) is 4.5/24 = 18.75%, the typical value for arid and semi-arid areas. The silicon type of PV panel is employed, which has a substantial share of the PV panel market. Both monocrystalline and polycrystalline types have a CO_2 emission coefficient, $C_{electricity}^{PVpanel}$ of 0.050 kg-CO_2/kWh at the highest,[29] and we adopted that value. Electricity required for seawater desalination (E_{water}) was assumed to be 6 kWh/m^3-H_2O.[30] The efficiency for the water electrolysis is 80%,[31] while the hydrogen extracted by the electrolysis is utilized to synthesize ammonia. The energy required for water electrolysis (E_{H2}) is 9.33 kWh/kg-NH_3, including desalination energy to obtain the necessary water. And referring to previous calculations by the process simulation software, ASPEN Plus©,[32,33] 0.39 kWh/kg-NH_3 was used for the cryogenic separation to extract nitrogen from the air (E_{N2}), and 0.78 kWh/kg-NH_3 for the ammonia synthesis based on extracted hydrogen and nitrogen (E_{NH3}).

Among the ammonia synthesis processes, the cryogenic separation of nitrogen and the reactor for ammonia require significant time for the start-up. The cryogenic separation takes 10 hours,[34] and the reactor needs 30 hours at least.[35,36] Therefore, nitrogen and ammonia cannot be efficiently produced if the plant is operated based on a daytime-only electricity supply from PV. For the constant operations of these two processes in this study, electricity from solar power is utilized with an operating rate of 18.75%, and the rest power of 81.25% is supplied by the grid. The CO_2 emissions from the grid-electricity generation were also taken into account. In other words, the daily PV electricity allocated for ammonia synthesis was further subdivided into 24 hours of water generation from seawater and water electrolysis to obtain the hydrogen amount required for ammonia synthesis, and 4.5 hours of nitrogen separation and ammonia synthesis. The electricity from the grid was assumed to be two patterns: thermal power generation based on natural gas and coal, where the output is readily controlled. The $LCCO_2$ emission factor for the electricity generation, $C_{electricity}^{Conv.}$, was 0.459 kg-CO_2/kWh for natural gas and 0.981 kg-CO_2/kWh for coal as the world average.[37]

2.3 Energy for water transport

In transporting water, the inner pipe diameter is assumed to be constant, and thus the velocity of water is also constant. The energy loss derived from the friction between the water and the pipeline is calculated by the lost hydraulic head, h (m), estimated from the Darcy-Weisbach equation below. Since frictional and sudden expansion losses at the inlet and outlet are inevitable, the inlet loss coefficient, ζ_i, and exit loss coefficients, ζ_e, are considered 0.5 and 1, respectively.

Since the flow velocity is constant, Bernoulli's principle indicates that the pressure difference between the outlet and inlet, Δp (Pa), and the city elevation, z (m), should be considered for the required energy. Δp alleviates the energy needed because the atmospheric pressure is lower on the outlet side than on the inlet side due to the elevation of the city. Therefore, the required energy for pumping and transporting water, $E_{transpoert}$ (kWh/day), was estimated using the following equation

$$E_{transport} = \frac{24W\rho g}{1000\eta_{pump}}\left(h + z + \frac{\Delta p}{\rho g}\right) \tag{1}$$

$$h = f\frac{l}{d}\frac{v^2}{2g} + (\zeta_i + \zeta_e)\frac{v^2}{2g} \tag{2}$$

$$v = \frac{W}{\pi(d/2)^2} \tag{3}$$

$$f = \frac{64}{Re}\ (Re < 3000) \tag{4}$$

$$f = \frac{0.3164}{Re^{1/4}}\ (3000 < Re < 100000) \tag{5}$$

$$f = 0.0032 + 0.221Re^{-0.237}\ (100000 < Re < 3000000) \tag{6}$$

$$Re = \frac{dv}{\nu} \tag{7}$$

$$\Delta p = 100((44.331514 - \mathrm{z}/1000)/11.880516)^{5.255877} - 101325 \tag{8}$$

where W is the water flow rate (m^3/s), ρ is the volume density of water (995.65 kg/m^3, 30°C), g is the gravitational acceleration (9.81 m/s^2), f is pipe friction coefficient (-), l is pipe length (m), d is pipe diameter (m), v is flow velocity (m/s), Re is Reynolds number (-), ν is the kinematic viscosity of water (8.01×10^{-7} m^2/s, 30°C), pump efficiency, η_{pump}, was set at 80%. Long-distance pipelines are expensive, and it is assumed that pre-existing electric power will be used to convey water to keep continuous operation and increase utilization efficiency. It is supposed that the electricity required for water transport is existing electricity derived from fossil fuels, and the amount of CO_2 emitted from the grid electricity generation is taken into account.

2.4 CO_2 emission from the pipeline construction

Concrete is employed for the pipeline material because it emits the lowest amount of CO_2.[38,39] Assuming reinforced concrete, commonly used for water pipes, 313 (kg-CO_2/m^3) was used as LCCO_2 emissions per volume of a pipeline, $C_{concrete}$.[40] The service life of the tunnel was assumed to be 30 years.[38] The CO_2 emission per day from the construction is calculated by dividing by the number of days. Pipelines cannot be constructed in a straight line, so we multiplied by 1.2 as an extension factor.[14] CO_2 emissions for installation and transportation of concrete pipelines were ignored because they are negligible.[38] The thickness of a concrete pipeline was estimated to be 1/12 of the inside diameter.[41] Therefore, the LCCO_2 emission per day from building the pipeline, B_{pipe} (kg-CO_2/day), is described as:

$$B_{pipe} = 1.2\pi l\left\{\left(\frac{d}{2}\right)^2 - \left(\frac{d}{2}\times\frac{11}{12}\right)^2\right\}C_{concrete}/(365\times 30) \tag{9}$$

The larger the inner pipe diameter, the less friction there is during water transport. However, this increases the excavation hole area and pipe thickness, inducing more LCCO_2 during construction. Then, there is a trade-off between construction and operation. In addition, the friction depends on the amount of water. To determine the diameter in this study, we assumed the case that the largest amount of water was transported, meaning all the PV electricity is distributed to seawater desalination. The reason for this is that the amount of water conveyed is controllable during operation, but the tunnel diameter cannot be readily changed. The amount of water required is expected to change with population fluctuations and seasons. Therefore, cases in which the maximum amount of water is transported are possible in practice. With this assumption, the tunnel diameter was determined to reduce the total amount of LCCO_2 from the construction and the operation. The amount of LCCO_2 emitted during the pipeline construction varies depending on the source of existing electricity. Thus, the internal diameters of the pipeline depend on the LCCO_2 emission factor of the power source, and are approximately 1.4 m for natural gas and 1.6 m for coking coal, respectively.

Since the pipeline construction needs a hole, we estimated the energy to excavate with a tunnel boring machine (TBM). The service life of the hole was assumed to be the same as the pipeline, 30 years.[38] The electrical power, E_{tunnel} (kWh/day), required for the tunnel bore was estimated using the following equation.[42,43]

$$E_{tunnel} = \frac{l}{3600}\left(\mathrm{F} + \frac{2\pi NT}{V}\right)/(365\times 30) \tag{10}$$

$$\mathrm{V} = \frac{-0.0464UCS + 5.6221}{6000} \tag{11}$$

$$\mathrm{F} = -548226\mathrm{V} + 22620 \tag{12}$$

$$\mathrm{T} = -95490\mathrm{V} + 4772.2 \tag{13}$$

where l is the pipeline length (m), F is TBM thrust (kN), T is TBM torque (kNm), and V is drilling speed (m/s). The uniaxial compressive strength (UCS) is set to 115 MPa as the value of the bedrock area and approximately the same value in deserts, etc.[44] N is rotation speed (rps), which was set to 0.0328 rps because the bedrock was assumed.[45] The LCCO_2 emissions from the boring energy were estimated assuming the usage of existing fossil fuel-based electricity.

2.5 CO_2 emission from the construction of grid and transfer of electricity

For the wires connecting the seaside desalination plant and the city, we assumed a typical example of one tension tower, five suspension towers, wires, insulators, and ground and shield wires for a 2 km line, which are capable of 420 kV power transmission. The LCCO_2 emission per wire length, C_{wire}, was 5.9×10^5 kg-CO_2/2km.[46] The service life of the wire was assumed to be 70 years.[46] The LCCO_2 emissions per day from the construction are calculated by dividing by the number of days. Thus, the $LCCO_2$ from building the wires, B_{wire} (kg-CO_2/day), were estimated by the following equation:

$$B_{wire} = C_{wire}\left(\frac{l}{2000}\right)/(365 \times 70) \tag{14}$$

As the transmission loss, the loss L (kWh/day) in the wire is estimated by the following equation.[47]

$$L = \frac{lR}{1000}\left(\frac{P}{\varphi}\right)^2/(1000 \times 3600 \times 24) \tag{15}$$

where P is the amount of power transmitted (100 MW), φ is the voltage (420 kV), R is the resistivity of the transmission line (Ω/km), and l is the length of the line (m), the same length of the pipeline. The amount of power transmitted was obtained from 100 MW of PV and 420 kV as the voltage considering the efficiency of the converter ($\eta_{converter}$ = 0.95), that of the transformer (η_{pump} = 0.995), and the resistivity, 0.0469 (Ω/km).[46]

2.6 Evaluation method of the reduced CO_2 emission and functional unit

The evaluation method in this study is the $LCCO_2$ decreased by the WEA scheme compared to producing all three with the conventional methods, D_{total} (kg-CO_2/day):

$$D_{total} = D_{water} + D_{electricity} + D_{ammonia} - I_{pipe\&wire} - I_{PVpanel} \tag{16}$$

$$D_x = C_x^{Conv.}Q_x^{Conv.} - C_x^{WEA}Q_x^{WEA} \tag{17}$$

$$Q_x^{Conv.} = Q_x^{Func.} - Q_x^{WEA} \tag{18}$$

$$\begin{gathered} Q_x^{WEA} = (R_x PV_{scale} PV_{out} \eta_{transformer} \eta_{converter} - L)\eta_{transformer}/E_x \\ R_{water} + R_{electricuity} + R_{ammonia} = 1 \\ I_{pipe\&wire} = C_{electricity}^{Conv.}(E_{transport} + E_{tunnel}) + B_{pipe} + B_{wire} \\ I_{PVpanel} = C_{electricity}^{PVpanel} PV_{scale} PV_{out} \\ where\ x = water, ammonia, and\ electricity \end{gathered} \tag{19}$$

where D_x is the $LCCO_2$ decreased by the WEA scheme compared to conventional methods in the production of x [= total (the total of the following three productions), water, ammonia, and electricity]. C_x^y is the $LCCO_2$ per quantity of product x prepared by method y [= Conv. (the conventional method), and WEA (the methods described in Section 2.2-2.5). The units are associated with Q_x^z]. Q_x^z is the quantity of product x associated with z [= Func. (functional unit) , Conv., and WEA. The unit is associated with E_x]. E_x is the electricity required for the product x in the WEA scheme, where $E_{electricity}$ (-) is one because electricity is supplied by PV power as it is and $E_{ammonia}$ (kWh/kg-NH_3) is $\{PV_{rate}(E_{N2} + E_{NH3}) + E_{H2}\}$ (see Section 2.2). R_x (-) is the ratio of allocated PV power to production of x. $I_{pipe\&wire}$ (kg-CO_2/day) is the $LCCO_2$ increased by the construction of pipeline and wire and the energy during the pipeline operation. $I_{PVpanel}$ (kg-CO_2/day) is the $LCCO_2$ increased by the PV panel, which provides power for the production of water, ammonia, and electricity. To avoid a double count, $C_{electricity}^{WEA}$ is zero. C_{water}^{WEA} is also zero because the electricity for desalination is from the PV electricity, included in $I_{PVpanel}$. Instead, Q_{water}^{WEA} (=$W \times 60 \times 60 \times 24$) increases $E_{transport}$ and B_{pipe} through Eq. (1-9). $C_{ammonia}^{WEA}$ considers the grid-electricity for the constant operation in ammonia synthesis (see Section 2.2), and is described as follows.

$$C_{ammonia}^{WEA} = C_{electricity}^{Conv.}(E_{N2} + E_{NH3})(1 - PV_{rate}) \tag{20}$$

The details of conventional production methods are as follows. Grid-electricity is assumed to be derived from thermal power generation and is analyzed in two patterns: fossil fuel is natural gas and coal. Their CO_2 emissions per electricity, $C_{electricity}^{Conv.}$ are the same value as presented in Section 2.2. As for $C_{water}^{Conv.}$, sewage and other water available in a city are assumed as the water resource, and the energy required to transport seawater through pipelines was not considered. RO is employed to make existing freshwater too, and the required energy was the same as the value in Section 2.2. $C_{ammonia}^{Conv.}$ is the $LCCO_2$ via the Haber-Bosch method based on existing fossil resources, and the average European value of 1.33 (kg-CO_2/kg-NH_3) was used.[48,49]

The functional unit in this study is set to the sum of the three products (electricity, freshwater, and ammonia), where the amount of each is calculated by the case that all of the PV electricity is allocated to only one product without considering water transport and transmission loss. It means that the amount of each electricity, freshwater, and ammonia is 450 (MWh/day), 7.50 × 10^4 (m^3-water/day), and 4.71 × 10^4 (kg-NH_3/day), respectively, estimated by the following equations with the parameters introduced in Section 2.2.

$$Q^{Func.}_{electricity} = PV_{scale}PV_{out}/E_{electricity} = 100 \times 4.5/1 = 450\ (MWh/day) \tag{21}$$

$$Q^{Func.}_{water} = PV_{scale}PV_{out}/E_{water} = 450 \times 10^3/6 = 7.50 \times 10^4\ (\mathrm{m}^3 - \mathrm{water}/day) \tag{22}$$

$$Q^{Func.}_{ammonia} = PV_{scale}PV_{out}/E_{ammonia}$$
$$= 450 \times 10^3/\{0.1875(0.39 + 0.78) + 9.33\} = 4.71 \times 10^4\ (kg - NH_3/day) \tag{23}$$

1350 MWh/day is required at least to produce all the functional units and the assumed PV power in this study (450 MWh/day) is not enough for that. The shortfall is compensated by the above existing production methods. Figure 3 shows, for example, the CO_2 emissions when all PV power is allocated to ammonia synthesis as in Case 1, taking into account the $LCCO_2$ generated in the pipeline/grid construction and the operation of water transportation/electricity transmission. The figure then shows an example of D_{total} (the pink-colored box), i.e., the reduced $LCCO_2$ emissions compared to the case where the functional units of electricity, freshwater, and ammonia are produced using the conventional method. Similarly, Case 2 shows the reduced CO_2 emissions when all 450 MWh/day of electricity is allocated to seawater desalination. In this way, the WEA scheme is evaluated byD_{total}.

When PV electricity is supplied to a city as electricity as it is, no pipeline or water transportation is required, and CO_2 emissions do not increase, and then no need to be analyzed. Therefore, the main focus of this study is the case in which PV-generated power is allocated to seawater desalination and ammonia synthesis.

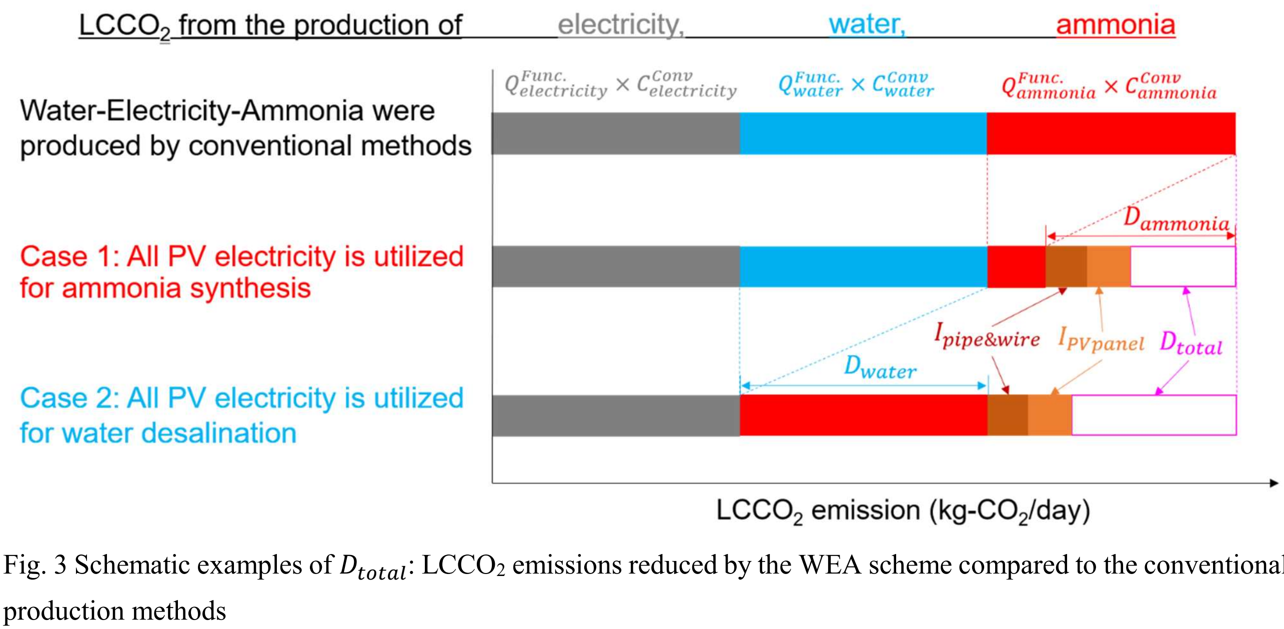

Fig. 3 Schematic examples of D_{total}: $LCCO_2$ emissions reduced by the WEA scheme compared to the conventional production methods

3. Result and Discussion

3.1 Sensitivity analysis

Sensitivity analyses are performed for the cases where all PV power is allocated to desalination (Fig. 4(a)) or ammonia synthesis (Fig. 4(b)). The influential parameters are increased or decreased by ±1%. The values in Section 2.2 are employed for each parameter. The CO_2 emission coefficient is assumed to be that of natural gas for electricity derived from fossil fuels. As the parameters not specified in Section 2.2, the elevation is considered to be about 800 m, which is the average elevation of the earth,[50] and the distance from the coast is 200 km, referring to the Suez Canal (193 km), one of the famous canals in the world.

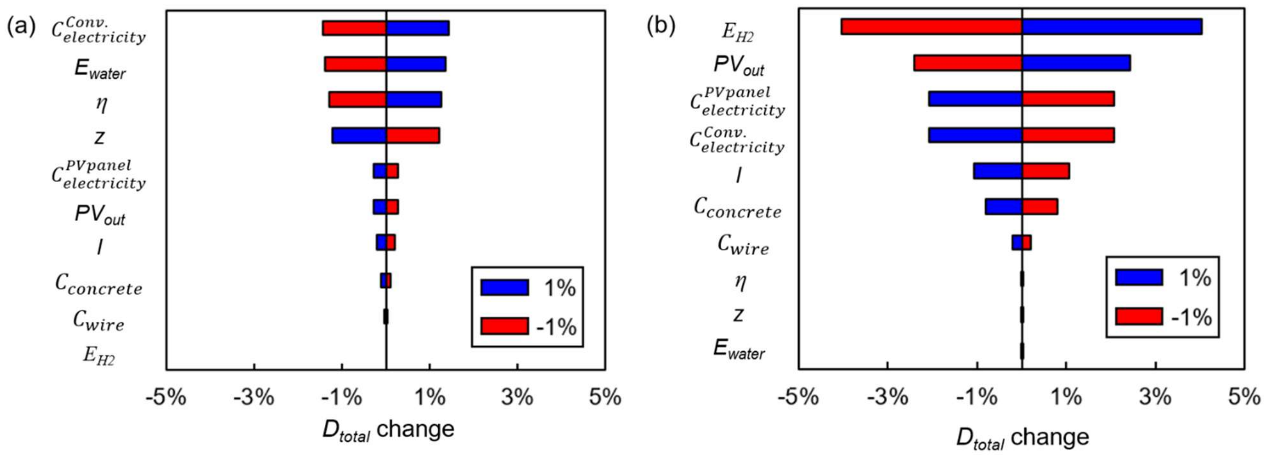

Fig. 4 The sensitivity analysis of the case that 100% of PV electricity is distributed to (a) desalination and (b) ammonia synthesis. Each parameter was varied by ±1% during the sensitivity analysis.

As shown in Fig. 4(a), the $LCCO_2$ emission factor of fuel-based electricity ($C_{electricity}^{Conv.}$) has the largest impact on the CO_2 emission from desalination, followed by desalination efficiency (E_{water}), pump efficiency (η), the elevation of a city (z), and the others. The four most influential parameters involve the potential energy that brings water to higher heights as follows. $C_{electricity}^{Conv.}$ and η is related to the power used to pump up the water. E_{water} determines the water volume to pump. z is directly related to the potential energy. Conversely, pipeline construction ($C_{concrete}$) and distance from the ocean (l) have been shown to have a tiny effect. For cities at higher elevations, it was demonstrated that allocating power to desalination is detrimental to reducing $LCCO_2$ emissions.

On the other hand, as Fig. 4(b) shows, the $LCCO_2$ emission from ammonia synthesis is affected the most by the efficiency of water electrolysis (E_{H2}). It is because ammonia synthesis requires a large amount of electric energy for water electrolysis (see Section 2.2). The following most influential parameters are the long-term average of a potential PV electricity generation (PV_{out}) and $LCCO_2$ emission from PV panels ($C_{electricity}^{PVpanel}$), related to the PV electricity. The next is $C_{electricity}^{Conv.}$ because ammonia synthesis requires continuous operation and electricity to support it, as described in Section 2.2. The following three parameters involved in pipeline length, l, $C_{concrete}$, CO_2 emission from grid construction (C_{wire}) has the subsequent large impact. The three parameters essential in desalination (E_{water}, η, and z) have minor effects on the $LCCO_2$ emissions in ammonia synthesis. It is because the water amount required for ammonia synthesis per electricity is tiny (0.1%) compared to seawater desalination since most of the energy in ammonia synthesis is consumed in water electrolysis. Therefore, it can be said that the $LCCO_2$ emissions related to the length of the pipeline are larger than the potential energy for ammonia synthesis. In other words, ammonia synthesis is advantageous for reducing CO_2 emissions in cities at higher elevations.

3.2 Quantitative assessment of the distance of cities from the sea and elevation for $LCCO_2$ emissions

In this section, we analyze the specific values of geographical criteria for the distance from the sea to a city and the elevation to reduce $LCCO_2$ emissions.

3.2.1 Distance from an inland city to the sea

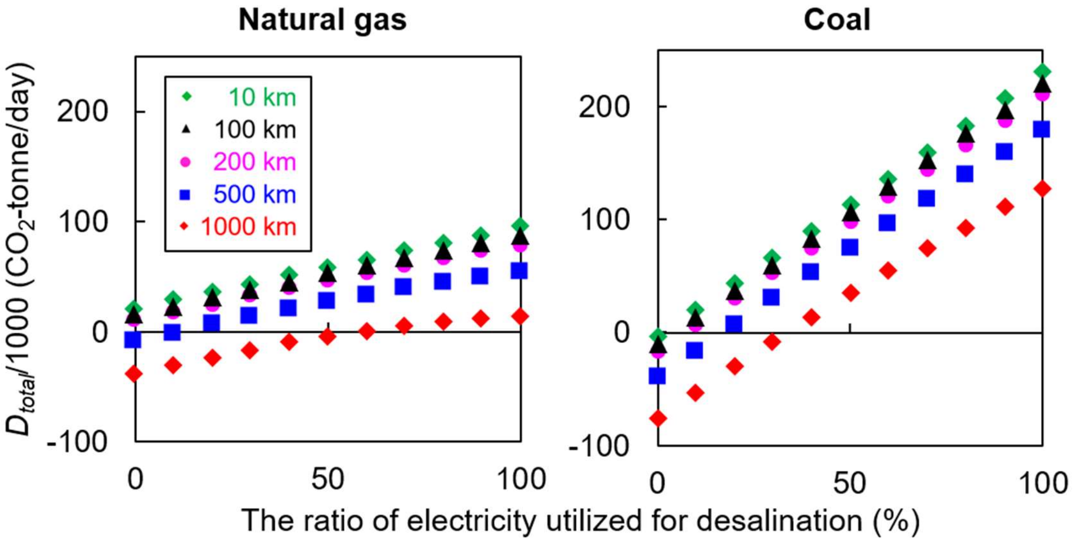

Fig. 5 D_{total} (y-axis) for a city with 800 m elevation varying the distance from the sea when PV electricity is allocated to desalination and ammonia synthesis. The two cases where fuel-based electricity is generated from natural gas and coal are shown. A positive value along the y-axis indicates that $LCCO_2$ emission is reduced by the WEA scheme compared to the production based on conventional methods. The x-axis is the percentage of electricity allocated to desalination, and the remaining electricity is given to ammonia synthesis.

We analyzed the cases where the elevation is fixed and the distance from the sea is varied to determine the specific length in which $LCCO_2$ emissions are reduced. Similarly, with Section 3.1, the elevation is fixed to 800 m as the global average elevation.[50] We examined the inland cities in the distance from the sea ranging from 1 to 1000 km. The whole arid/semi-arid region of Australia is within 1000 km from the coast. Even the pole of inaccessibility in Africa, which also has a vast arid/semi-arid region, is 1814 km. Therefore, the analysis within 1000 km is sizable to analyze the land area on the earth. Figure 5 shows D_{total} when the ratio of PV electricity allocated to seawater desalination and ammonia synthesis is varied. Since Section 3.1 indicates that $LCCO_2$ emission from fuel-based electricity generation significantly impacts seawater desalination and ammonia synthesis, two natural gas or coal cases are analyzed. The results show that even for a city with 1000 km inland, $LCCO_2$ emissions can be reduced if desalination receives more than 60% of PV electricity for the natural gas case and 40% for the coal case.

Figure 6 shows the breakdown of $LCCO_2$ emissions from the WEA scheme in cases where PV power allocation to desalination is 0%, 50%, and 100%. The decreased energy for pumping water due to the difference in atmospheric pressure and the loss at the inlet/outlet is a tiny percentage of the total and almost invisible. Unless PV electricity is allocated to the ammonia synthesis mainly, a huge proportion of the energy is spent on water transport in the vertical direction, the same tendency as the sensitivity analysis results in Section 3.1. It can also be seen that the amount of $LCCO_2$ emissions is influenced by the water transport vertically more largely than horizontally, even for very long horizontal distances of 1000 km. Therefore, the positional energy of water is essential, and the elevation of the city is more important than the distance from the coast as a factor influencing $LCCO_2$ emissions.

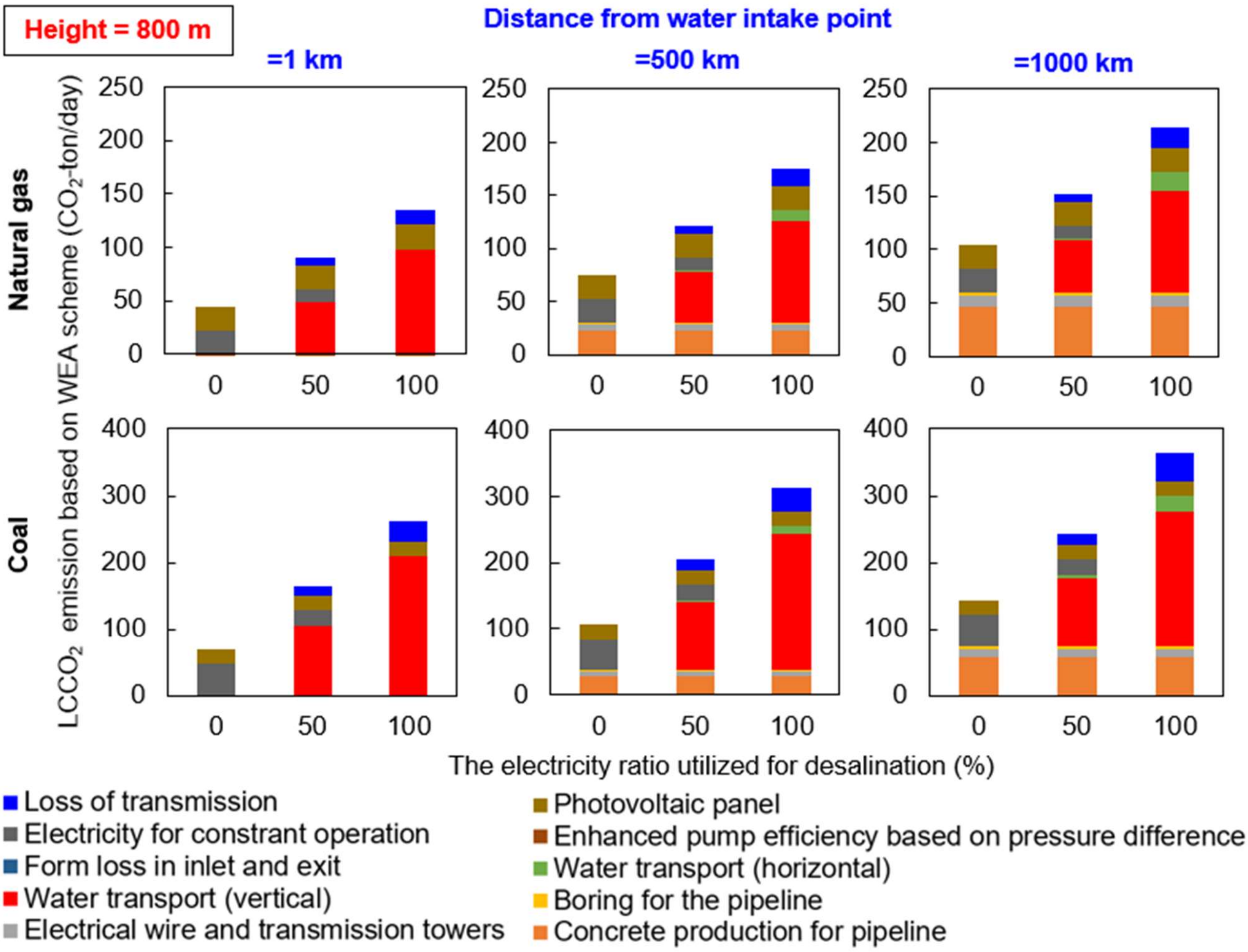

Fig. 6 The breakdown of CO_2 emissions from the WEA scheme at fixed elevation and varying distances from the sea. The PV power allocation to desalination is 0%, 50%, and 100%, and natural gas and coal are assumed as the fuel to generate grid electricity.

The construction of electric lines and transmission losses occupy some weight in $LCCO_2$ emission. However, the weight is still small, 25% at most, compared to the energy of water transportation and the total $LCCO_2$ emissions from pipeline construction. If the seawater is supplied to cities without desalination, the recovery rate of RO is approximately 50%, and thus twice the energy is required for seawater transportation. Moreover, two pipelines must be constructed to return the concentrated seawater to the sea. In other words, as assumed in this study, it is more efficient to build a pipeline and an electric line from the desert to the sea, desalinate seawater at the seashore, dispose of brine water on the spot, and then transport only freshwater. However, there are also possibilities to devise ways to increase the recovery rate and to use hydroelectric power generation using concentrated seawater or pumped storage power generation. In addition, the construction of PV and thermal power plants at each of the desalination plant and ammonia synthesis plant locations can be considered. The cases without power lines need further studies.

3.2.2 Elevation of a city

In this section, we analyzed the case where the distance of a city from the sea is fixed, and the elevation is varied to determine the specific height to which $LCCO_2$ emissions can be reduced. For example, the average elevation in the Sahara Desert, the largest desert in Africa, is about 300 m. Still, the maximum height of the present study is set to 2000 m to analyze alpine cities. Since all cities with a population of 1 million or more are below 2000 m except for the top 10 cities in the world,[51], the elevation up to 2000 m is sufficient to evaluate cities in high altitude areas.

Similarly in Section 3.2.1, two ways are shown for the case of using existing electricity derived from natural gas or coal. In the same way as Fig. 5, Figure 7 shows the reduction in CO_2 emissions when the supply of PV power as electricity is 0%, and the ratio of PV electricity allocation to seawater desalination and ammonia synthesis is changed.

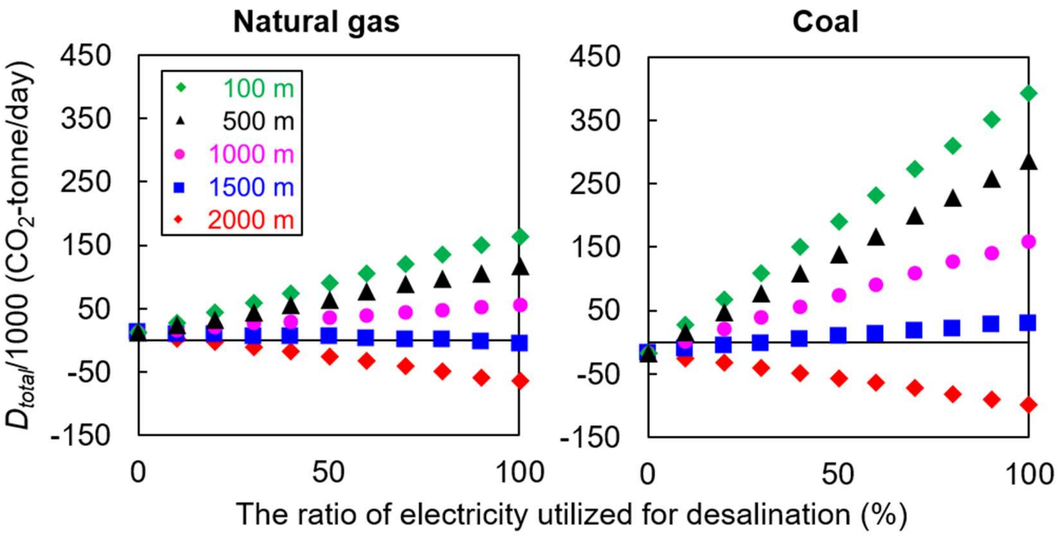

Fig. 7 D_{total} for a city with a 200 km distance from the sea and varying elevation when PV electricity is allocated to desalination and ammonia synthesis. The two cases where fuel-based electricity is generated from natural gas and coal are shown. The meanings of the horizontal and vertical axes are the same as in Fig. 5.

Fig. 7 indicates that, regardless of natural gas or coal, if the distance from the sea is 200 km, CO_2 emissions are reduced by allocating to seawater desalination until the elevation is 1500 m. However, over 1500 m height, ammonia synthesis is advantageous rather than desalination. Figure 8 shows the breakdown of CO_2 emissions for the WEA scheme under these land conditions. The reason for advantage is that vertical transport of water is the dominant energy consumption. The cause of the reversing benefits between ammonia synthesis and seawater desalination at a certain height is discussed here.

When PV power is allocated to seawater desalination without considering water transport and electricity transmission, $LCCO_2$ emissions effectively drop to about 6~13% (varied by the fuel for grid electricity). However, as discussed until here, the potential energy of water is dominant, and thus pumping up water at high altitudes cancels the reduced $LCCO_2$ emissions.

On the other hand, ammonia synthesis requires a smaller amount of water and is less affected by elevation. However, the PV electricity-derived synthesis method for ammonia is ineffective in reducing $LCCO_2$ and is 0.53 kg-CO_2/kg-NH_3, 39% of the emission from the conventional synthesis: 1.33 kg-CO_2/kg-NH_3. It is because the existing synthesis directly utilizes fossil resources rather than electricity and is very energy efficient. Hence, to reduce CO_2 emission, ammonia synthesis is not favorable rather than desalination at low altitudes.

Based on this trade-off, seawater desalination is advantageous until the elevation exceeds about 1500 m above sea level, while ammonia synthesis is favored at higher elevations. Also, at around 1500 m, $LCCO_2$ emissions are approximately ±0, no matter how the PV power is distributed. Fig. 9 shows a world map, with the areas below 1500 m elevation shown in blue. Except for some regions such as Peru, Chile, and Mexico, the coastal area within 200 km from the sea, the height usually is 1500 m. Therefore, the coastal deserts are worth considering for the WEA scheme.

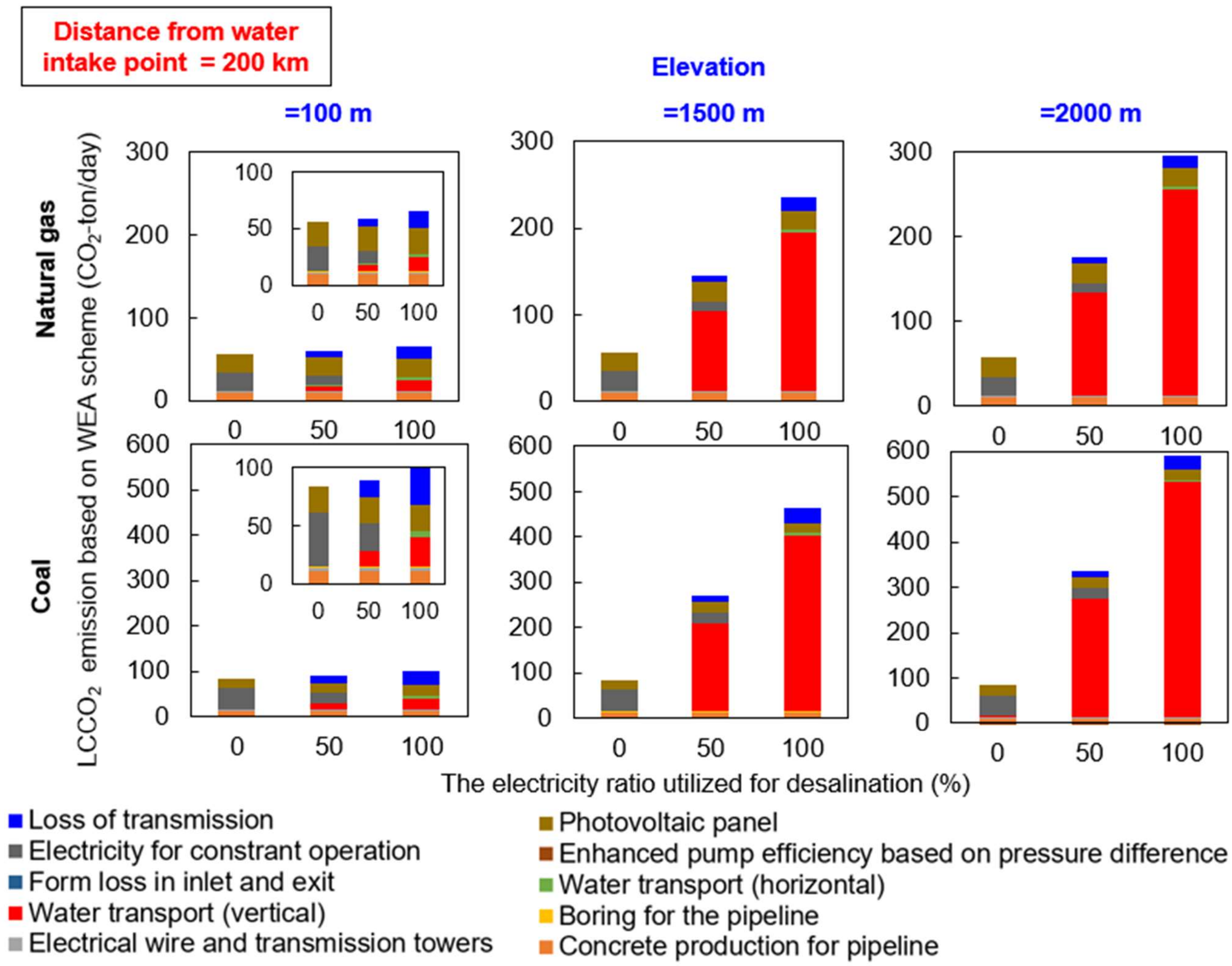

Fig. 8 The breakdown of $LCCO_2$ emissions from the WEA scheme at the fixed distance from the sea and varying elevations. The PV power allocation to desalination is 0, 50, and 100%, and natural gas and coal are assumed as the fuel to generate grid electricity.

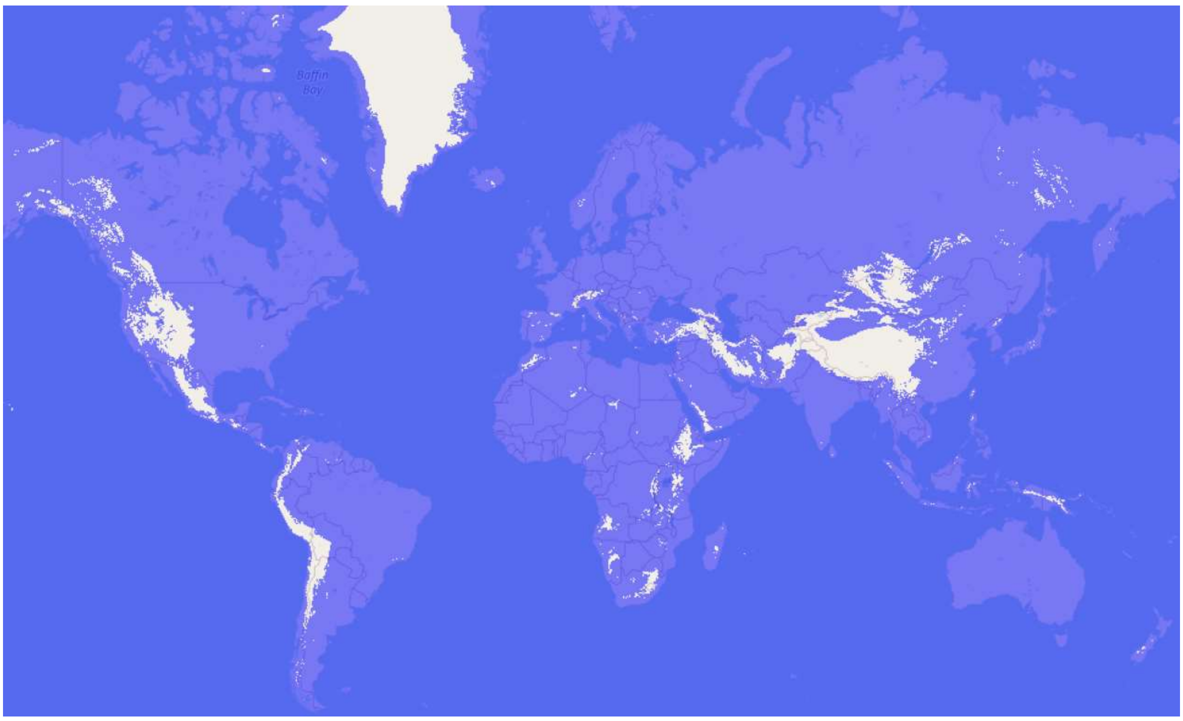

Fig. 9 The world map showing elevations below and above 1500 m in blue and white, rexpectively[52]

3.3 $LCCO_2$ emission from the WEA Scheme in each specific region

This section estimates the $LCCO_2$ emission from the WEA scheme in the actual areas. The $LCCO_2$ emission factors for fuel-based electricity employs an average value in each country.

3.3.1 The Gobi Desert

From the results in Sections 3.2.1 and 3.2.2, the WEA scheme can reduce $LCCO_2$ emissions in a wide range of geographical conditions even if 0% of the PV electricity is supplied as electricity as it is. However, in geographies distant from the ocean and at higher elevations, $LCCO_2$ emissions might increase no matter how desalination and ammonia synthesis are allocated. For example, the Gobi Desert, which straddles China and Mongolia, is about 2000 km from the sea and is located 1500 m above sea level. Currently, there is not a huge demand for that water or electricity in these areas, but it may become necessary in the future, and thus we examined the desert. $C_{electricity}^{Conv.}$ was set to 0.80 (kg-CO_2/kWh), the average of 0.84 (kg-CO_2/kWh) for Mongolia and 0.76 (kg-CO_2/kWh) for China.[53]

As shown in Fig. 10, when the electricity supply is set to 0%, no matter how PV electricity is allocated between ammonia synthesis and seawater desalination, $LCCO_2$ emissions are not reduced but rather increase. On the other hand, when 30% of the PV power is supplied as electricity, $LCCO_2$ emissions can be reduced by allocating 30% or more power to desalination. If more than 40% of PV power is provided as electricity, $LCCO_2$ emission decreases regardless of the PV power allocation between ammonia synthesis and seawater desalination. Interestingly, a city at a high elevation and far from the sea is more likely to reduce $LCCO_2$ emissions by allocating a certain amount of PV power between seawater desalination and ammonia synthesis. In Fig. 10, the most reduction in $LCCO_2$ emissions can be achieved when about 70% of the power is allocated to desalination. This optimum curve appears because of a balance between the large $LCCO_2$ decreasing effect of desalination and the shrink of the transported water amount due to increased PV electricity allocation to ammonia synthesis.

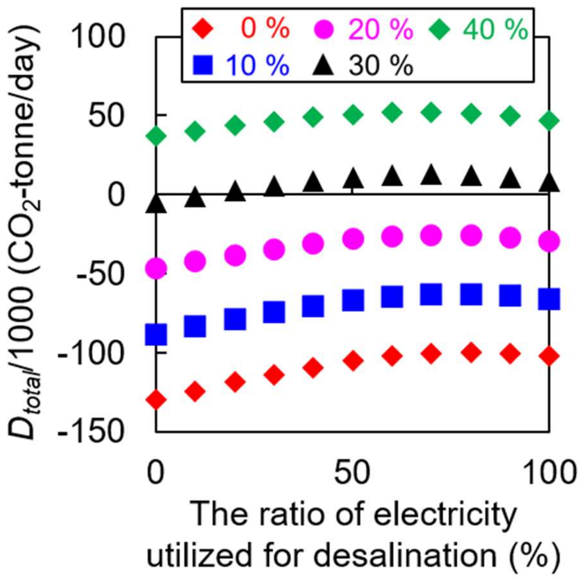

Fig. 10 D_{total} in the Gobi Desert. The legend shows the supply percentage of PV power as electricity as it is. With defining the rest of PV power as 100%, the horizontal axis is the percentage of PV electricity allocated to desalination, while the remaining is distributed to ammonia synthesis.

3.3.2 The Sahara Desert

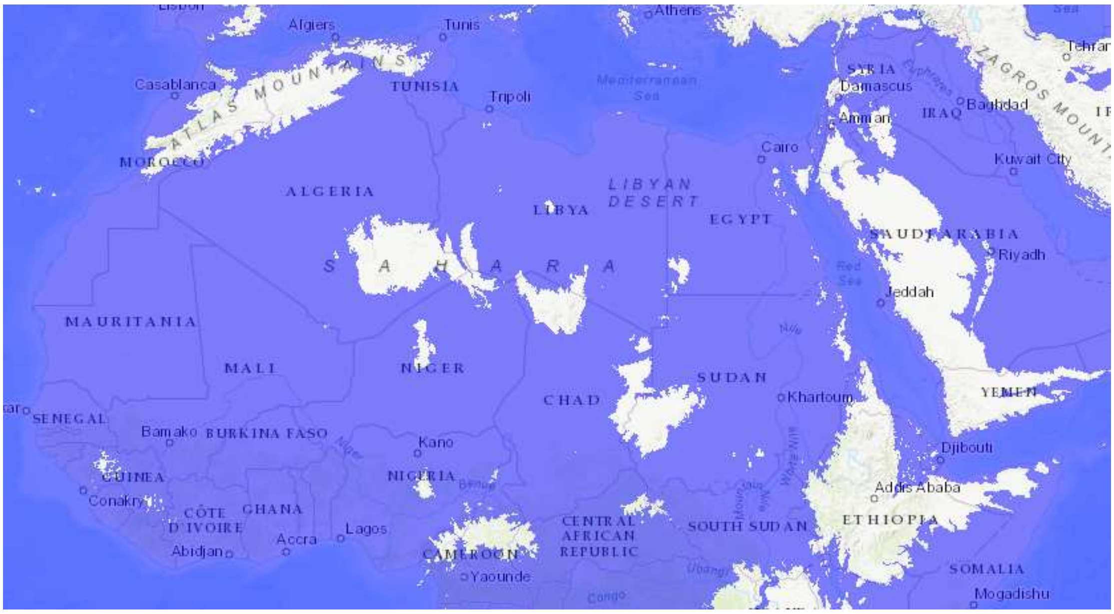

Fig. 11 The map of North Africa showing the areas in white more than 800 m above sea level[52]

Here, we analyze the Sahara Desert in Africa, the largest desert in the world. Fig. 11 shows a map of north Africa, white-colored above 800 m above sea level. The elevation is mostly below 800 m, except for the Atlas Mountains and the central region of the Sahara Desert. For example, a city in the center of the Sahara, Agadez in Niger, is 520 m above sea level, and the shortest way to the coast is about 1300 km, even though it cannot circumvent Nigeria. Referring to the $LCCO_2$ emission factor for electricity in Niger of 0.53 kg-CO_2/kWh,[53] we apply the WEA scheme to Agadez. It can be seen that even if the supply as electricity is 0%, $LCCO_2$ emissions are reduced if the share of desalinated seawater is more than 30%, as shown in Fig. 12. If the supply as electricity is 20% or more, $LCCO_2$ emissions can be reduced no matter how the remaining electricity is allocated. Since the geographical conditions of the countries around the center of the Sahara Desert are similar to Agadez, $LCCO_2$ emissions can be reduced if the allocation ratio of electricity supply, desalination, and ammonia synthesis is adjusted as described above. In other words, even if desalinated water and ammonia as fertilizer are delivered to the vast land area of the Sahara Desert, the WEA scheme can reduce $LCCO_2$ emissions. In particular, the largest city in the Sahara Desert is Nouakchott in Mauritania, which faces the sea and is surrounded by desert. The scarcity of water is expected to increase because of the significant growth in population. Therefore, it is worthwhile to consider the WEA scheme.

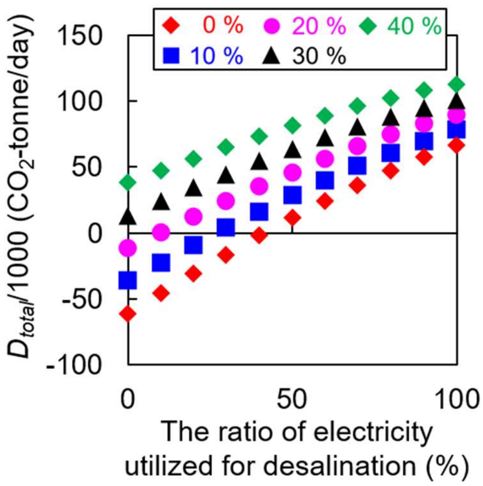

Fig. 12 D_{total} in the Agades. Legend, the meaning of each axis is the same as in Fig. 10

3.3.3 Australia

Figure 13 shows the map of the Australian continent where the area above 800 m is colored in white. Since almost the entire Australian continent is below 800 m and the distance from the center of the continent to the coast is about 1000 km, it can be said that the WEA scheme can be applied to reduce the $LCCO_2$ amount.

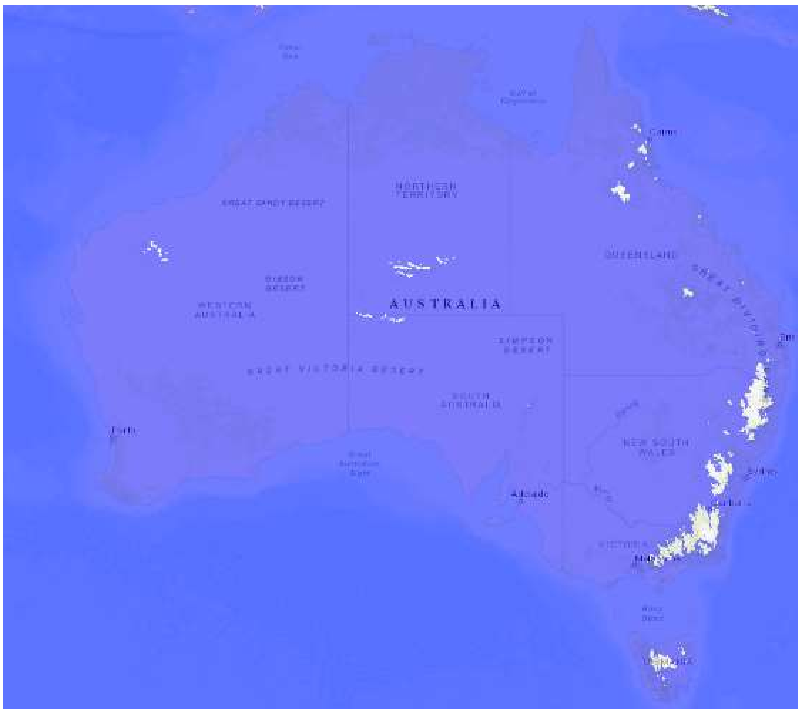

Fig. 13 The map of the Australian continent showing the areas in white more than 800 m above sea level[52]

3.3.4. Mexico City

Mexico City, located in a highland area, 2250 m above sea level and approximately 250 km from the ocean, suffers from water shortages because its population exceeds its environmental capacity. The WEA scheme is applied to Mexico City, and the amount of $LCCO_2$ reduction is examined. 0.45 kg-CO_2/kWh was used as the $LCCO_2$ emission factor for fuel-based electricity in Mexico.[53] Figure 14 indicates when the supply of electricity as electricity is 0%, the $LCCO_2$ emissions increases unless more than 90% of the PV electricity is allocated to ammonia synthesis. However, as the electricity supply increases, $LCCO_2$ emissions can be reduced even if more PV electricity is given to desalination. 40% of the electricity supplied is enough to reduce $LCCO_2$ emissions no matter how allocated the remaining electricity is. Mexico City has already pumped water from wells as deep as 1900 m,[54] and then there is a possibility to be realized. In conclusion, even at a high altitude and distance from the coast, such as Mexico City, the WEA scheme can reduce $LCCO_2$ emissions overall by adjusting the distribution of power supply sources with electricity, desalination, and ammonia synthesis.

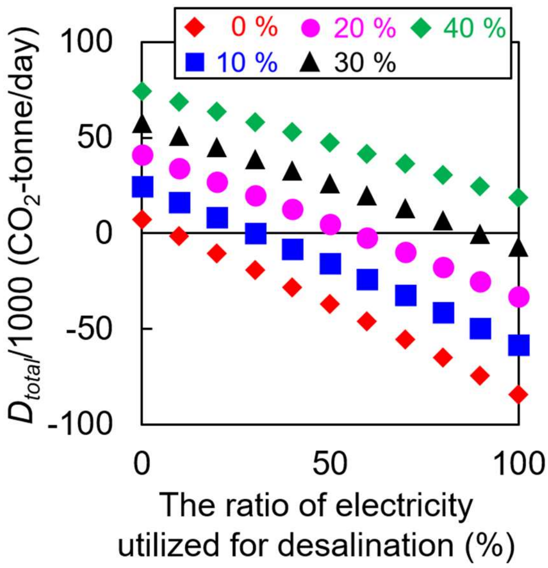

Fig. 14 D_{total} in Mexico City. Legend and the meaning of each axis are the same as in Fig. 10

3.3.5 Deserts below sea level

The results clarified that the WEA scheme effectively decreases the $LCCO_2$ emission even in inland deserts and extreme highlands. Meanwhile, some deserts exist below sea level, for example, the basin around the Dead Sea in Jordan: -400 m, Lake Eyre in southern Australia: −9 (m), the Kattera lowlands in Egypt: −40 m, Lake Gerid in Tunisia: −20 m, Lake Merlir in Algeria: −40 m, Turfan in China Land: −154 m, and Mexicali in Mexico: almost 0 m.[52] The desert below 0 m sea level is preferable in reducing $LCCO_2$ emission because they can use the potential energy to transport water the other way round. These are favorable conditions for applying the WEA scheme.

3.3.6. Limitation

In Section 3.3, the WEA scheme compensates for $LCCO_2$ by replacing fossil resource-based electricity with PV-based electricity. In other words, if PV generation is not within the variable capacity of thermal power generation, PV-based electricity generation will be oversupplied. If the WEA scheme is applied and allocates PV power to electricity, the electricity amount should be within the variable capacity of thermal power generation in each country as a limitation of this approach.

4. Conclusion

We proposed the WEA scheme to supply electricity, freshwater, and ammonia, which are essential for human beings, and analyzed the case of applying the WEA scheme to inland cities in arid/semi-arid regions by using solar power (PV), seawater, and pipelines. It was found that allocating PV electricity to seawater desalination is advantageous for reducing $LCCO_2$ emissions in lowland areas, while one to ammonia synthesis is more advantageous in highland regions. And even when supplying cities located in extreme highlands and inland areas, it was found that adjusting the distribution of the three products can reduce overall $LCCO_2$ emissions.

PV generation can be highly efficient in arid/semi-arid regions, but there is a huge demand for freshwater and food rather than electricity as it is. The WEA scheme, where PV electricity is the power source and is expected to be cheaper, will contribute to securing freshwater and promoting agriculture, thereby improving the quality of people's lives, and will become important in the future. Further studies will evaluate the feasibility of the WEA scheme by assessing several aspects, such as the economic side.

Nomenclature

B_{pipe}: LCCO$_2$ emission per day from building the pipeline, (kg-CO$_2$/day)

B_{wire}: LCCO$_2$ from building the wires (kg-CO$_2$/day)

$C_{concrete}$: LCCO$_2$ emissions per volume of a pipeline (kg-CO$_2$/m^3)

C_{wire}: LCCO$_2$ emission per wire length (kg-CO$_2$/2km)

$C_{ammonia}^{Conv.}$: LCCO$_2$ emission factor for producing ammonia with the conventional method (kg-NH$_3$/kWh)

$C_{electricity}^{Conv.}$: LCCO$_2$ emission factor for producing electricity with the conventional method (kg-CO$_2$/kWh)

$C_{water}^{Conv.}$: LCCO$_2$ emission factor for producing water with the conventional method (kg-CO$_2$/kWh)

$C_{electricity}^{PVpanel}$: LCCO$_2$ emission coefficient of PV panel (kg-CO$_2$/kWh)

$C_{ammonia}^{WEA}$: LCCO$_2$ emission factor for producing ammonia with the method in the WEA scheme (kg-CO$_2$/kWh)

$C_{electricity}^{WEA}$: LCCO$_2$ emission factor for producing electricity with the method in the WEA scheme (kg-CO$_2$/kWh)

C_{water}^{WEA}: LCCO$_2$ emission factor for producing water with the method in the WEA scheme (kg-CO$_2$/kWh)

d: pipe diameter (m)

D_{total}: LCCO$_2$ decreased by the WEA scheme compared to producing water, electricity, and ammonia with the conventional methods (kg-CO$_2$/day)

$D_{ammonia}$: LCCO$_2$ decreased by the WEA scheme compared to producing ammonia with the conventional method (kg-CO$_2$/day)

$D_{electricity}$: LCCO$_2$ decreased by the WEA scheme compared to producing electricity with the conventional method (kg-CO$_2$/day)

D_{water}: LCCO$_2$ decreased by the WEA scheme compared to producing water with the conventional method (kg-CO$_2$/day)

$E_{ammonia}$: electricity required for whole processes of ammonia synthesis (kWh/kg-NH$_3$)

E_{water}: electricity required for seawater desalination (kWh/m^3-H$_2$O)

$E_{transport}$: energy required for pumping and transporting water (kWh/day),

E_{tunnel}: electricity to bore a tunnel (kWh/day)

E_{H2}: electricity required for water electrolysis to obtain hydrogen gas (kWh/kg-NH$_3$)

E_{N2}: electricity required for the cryogenic separation to extract nitrogen gas from the air (kWh/kg-NH$_3$)

E_{NH3}: electricity required for the ammonia synthesis reactor (kWh/kg-NH$_3$)

f : pipe friction coefficient (-)

F: TBM thrust (kN)

g: the gravitational acceleration (9.81 m/s^2)

h: the lost hydraulic head (m)

$I_{pipe\&wire}$: LCCO$_2$ increased by the construction of pipeline and wire and the energy during the pipeline operation (kg-CO$_2$/day)

$I_{PVpanel}$: LCCO$_2$ increased by the PV panel (kg-CO$_2$/day)

l: pipe length (m)

L: the transmission loss (need modification)

P: amount of power transmitted (MW)

PV_{scale}: PV scale (MW)

PV_{out}: long-term average of a potential PV electricity generation (kWh/kWp/day)

PV_{rate}: rate of PV operation (-)

$Q_{ammonia}^{Func.}$: ammonia quantity of functional unit (kg-NH$_3$/day)

$Q_{electricity}^{Func.}$: electricity quantity of functional unit (kWh/day)
$Q_{water}^{Func.}$: water quantity of functional unit (m^3-H_2O/day)
$Q_{ammonia}^{Conv.}$: ammonia quantity produced by the conventional method (kg-NH_3/day)
$Q_{electricity}^{Conv.}$: electricity quantity produced by the conventional method (kWh/day)
$Q_{water}^{Conv.}$: water quantity produced by the conventional method (m^3-H_2O/day)
$Q_{ammonia}^{WEA}$: ammonia quantity produced by the method in the WEA scheme (kg-NH_3/day)
$Q_{electricity}^{WEA}$: electricity quantity of functional unit produced by the method in the WEA scheme (kWh/day)
Q_{water}^{WEA}: water quantity produced by the method in the WEA scheme (m^3-H_2O/day)
R: resistivity of a transmission line (Ω/km)
$R_{ammonia}$: the ratio of allocated PV power to ammonia (-)
$R_{electricity}$: the ratio of allocated PV power to electricity (-)
R_{water}: the ratio of allocated PV power to water (-)
Re: Reynolds number (-)
T: TBM torque (kNm)
UCS: uniaxial compressive strength (MPa)
v: flow velocity (m/s)
V: drilling speed (m/s)
W: water flow rate (m^3/s)
z: city elevation(m)
ρ: the volume density of water (995.65 kg/m^3, 30°C)
ζ_i: inlet loss coefficient (-)
ζ_e: loss coefficients (-)
Δp: pressure difference between the outlet and inlet (Pa)
ν: the kinematic viscosity of water (8.01×10^{-7} m^2/s, 30°C)
$\eta_{converter}$: converter efficiency (-)
η_{pump}: pump efficiency (-)
$\eta_{transformer}$: transformer efficiency (-)
φ: voltage of power transmitted (kV)

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