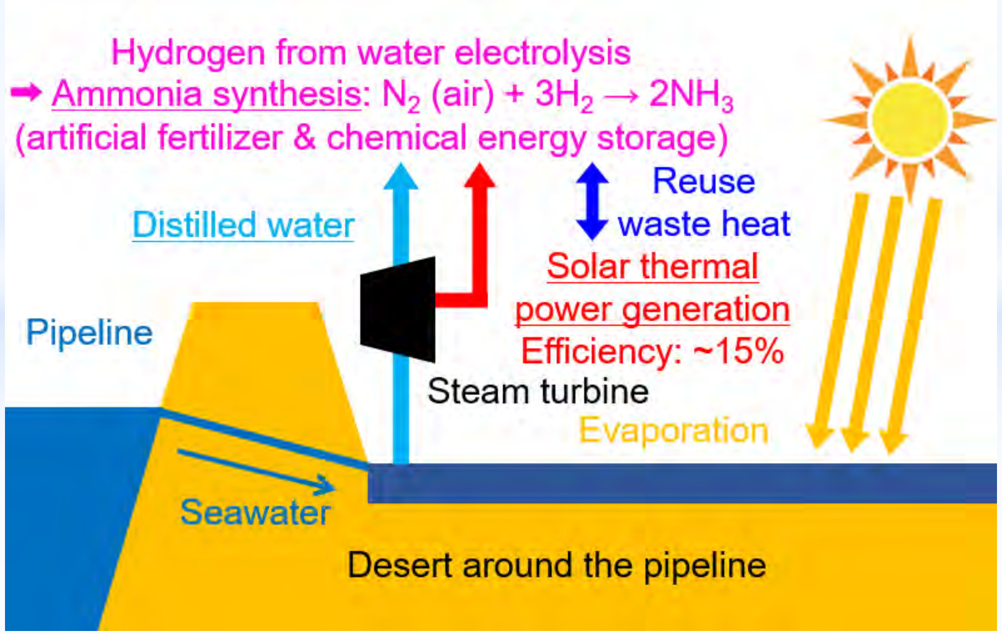
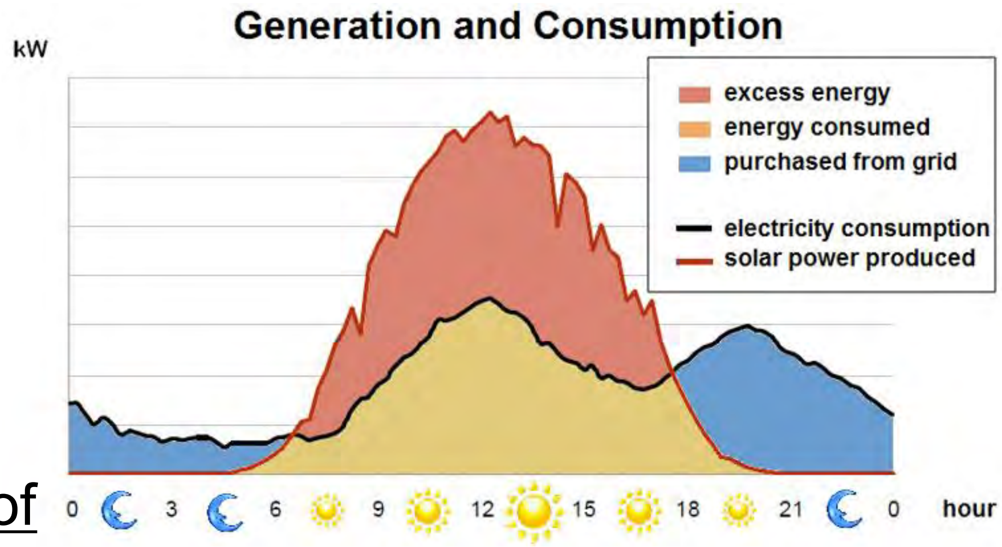
Sustainable and economical production scheme of Water-Electricity-Ammonia Nexus using seawater and sunlight in deserts below 0 m sea level



Takaya Ogawa, Ph.D., Assistant Professor
Graduate School of Energy Science, Kyoto University, Japan

Background: Excess electricity

- Electricity from renewable energy is important for the reduction of CO_2 emission
- Cheap electricity based on sunlight is getting feasible
  - Ex. 1.04 ¢/kWh (Saudi Arabia, 600 MW, announced April 2021) https://commercialsolarguy.com/lowest-solar-power-prices-in-the-world/
  - Arid/semi-arid region is suitable
- Excess electricity is wasted in the daytime
  - Demand of electricity in a desert is not huge
- Battery is useful, but generally too expensive
- Arid/semi-arid region normally requires water/food rather than electricity
- Excess electricity can be utilized for the production of Potable water and Ammonia (artificial fertilizer and energy carrier)

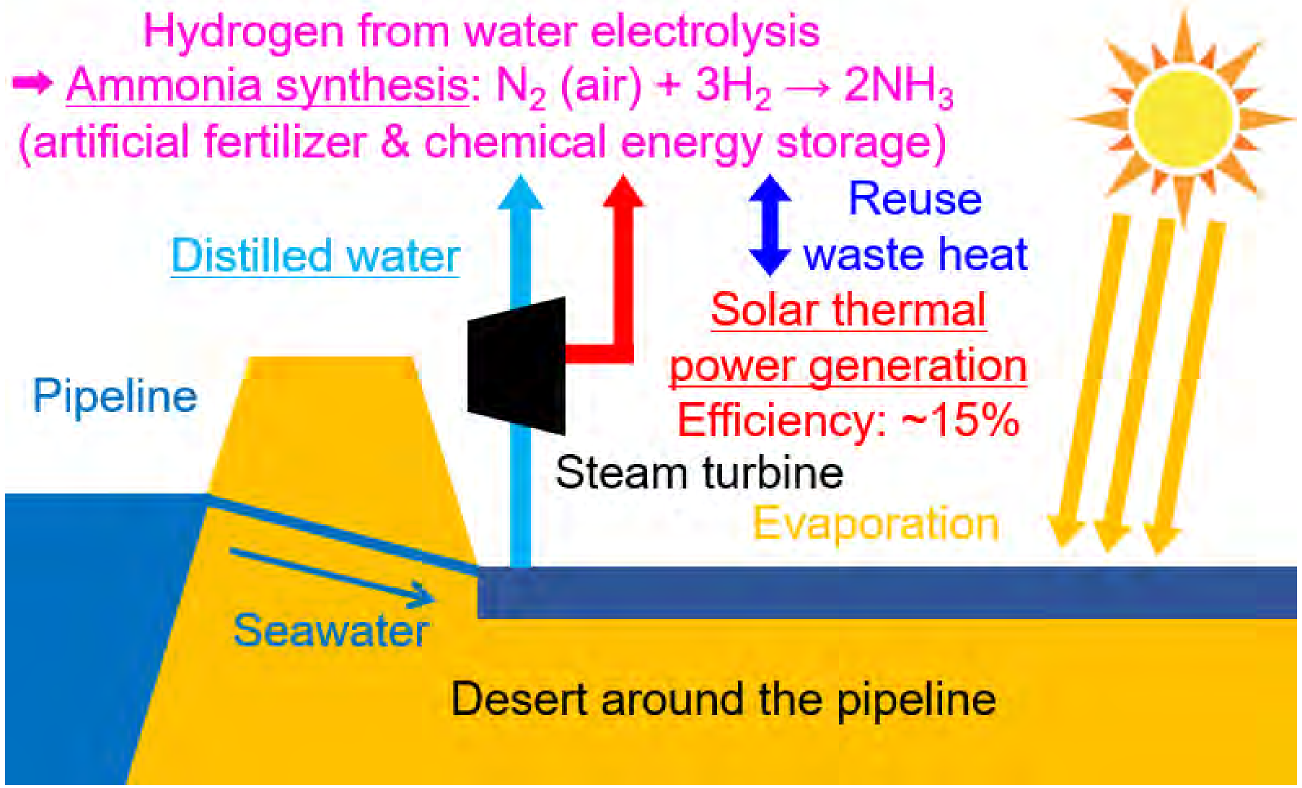


→ **Water-Electricity-Ammonia Nexus (WEA scheme) using Seawater and Sunlight in Arid/semi-arid region**

- **Total number of process is reduced**
- **Energy efficiency is enhanced by reusing waste heat**

➡ High profitability

Scheme of WEA production (an example)



- Water & electricity can be generated together
  – Total number of process is decreased
- Waste heat (& excess electricity) can be converted to ammonia
  – Energy efficiency is increased
- Pipeline from the sea to a city must be constructed

The desert below 0m sea level: Around Dead sea in Jordan

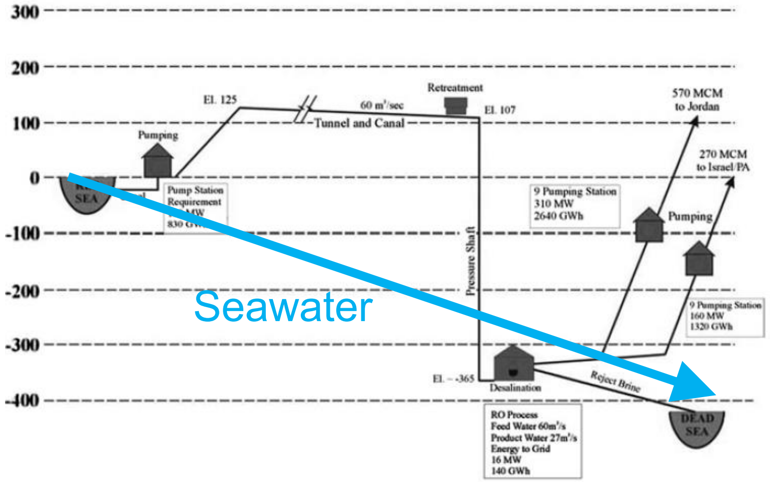
Background of Jordan

*World bank data

- Population: 6,320,000 (2012) → 9,700,000 (2017)

  *Refugees from surrounding countries
- Huge demand for water & food
- Pipeline will be constructed for “Red Sea-Dead Sea canal project”
- A lot of sunlight and infinite seawater (+ air)
  - 1/8 of land area in Jordan receives sunlight of 23 PWh/year = Electricity consumption in the world@2019
  - Potential to export ammonia as an energy carrier
- No energy requirement for seawater transportation

Red sea

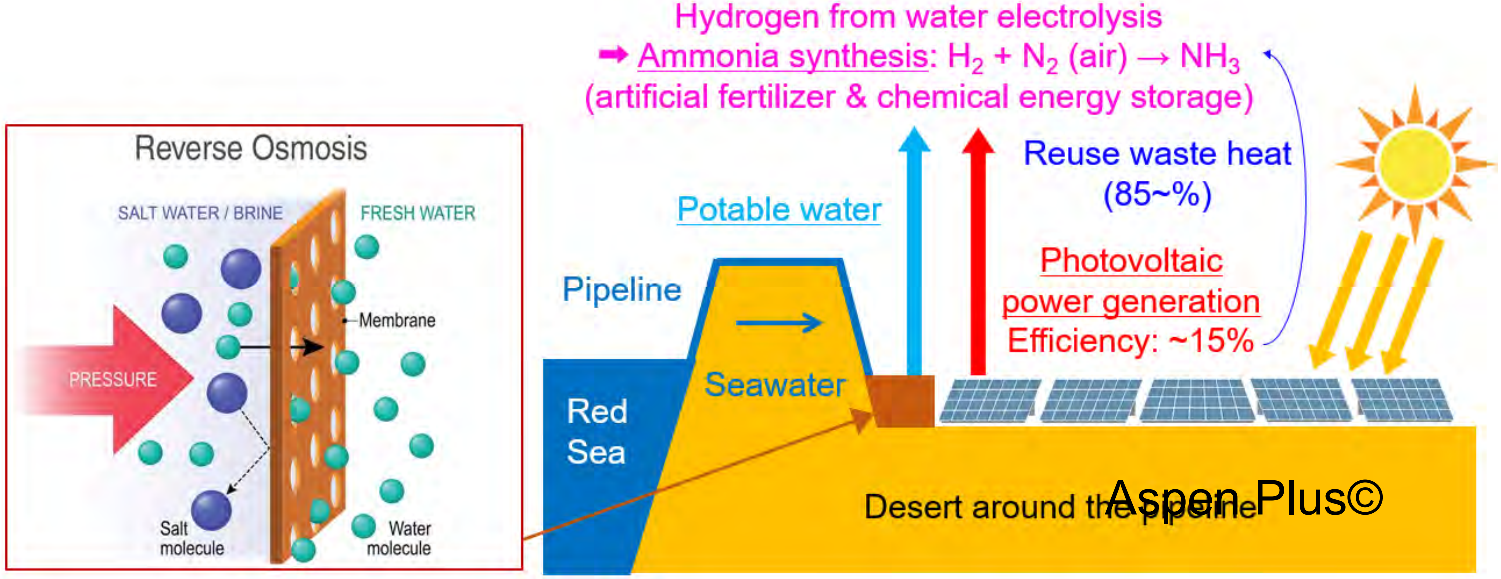


Dead sea:
Below −400m
sea level

https://www.nrdc.org/onearth/could-water-red-sea-help-revive-dead-sea

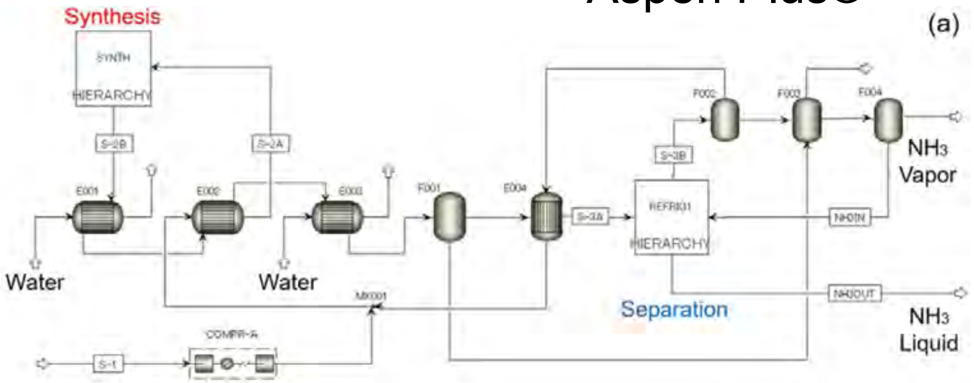
“The Red Sea–Dead Sea Canal: Its Origin and the Challenges it Faces”, DOI: 10.1007/978-3-642-14779-1_5

Scheme of WEA scheme (pattern B, C, D...)



https://www.watertechonline.com/metering-pumps-reverse-osmosis-water-treatment/

Aspen Plus©



$$C_j = C_{j,fix} + LM \times \frac{\text{CEPCI in 2019}}{1000} \times AF \times C_{j,ref} \times \left(\frac{s_j}{s_{ref}}\right)^{n_j}$$

Int. J. Hydrog. Energy **2021**, *46*, 28840-28854.

- Several patterns are possible
- Currently, we investigate the cost / the amount of CO_2 emission
- Other locations will be also examined
  - Cities facing to a desert and to the sea
  - Other deserts under 0 m sea level (ex. Lake Eyre in Australia)
- We are also examining new catalysts for NH_3 synthesis.

Future plan: Agriculture at Gulf of Aqaba

- Recommendation from researchers in the University of Jordan:
  - Pilot plant of WEA scheme should be constructed at Gulf of Aqaba
- Gulf of Aqaba: Water intake point of Red Sea-Dead Sea canal
- <u>Demonstration: Agriculture at Gulf of Aqaba</u>

Benefits of the crop increased by water and ammonia	−	Cost of water and ammonia supply based on WEA scheme	> 0?

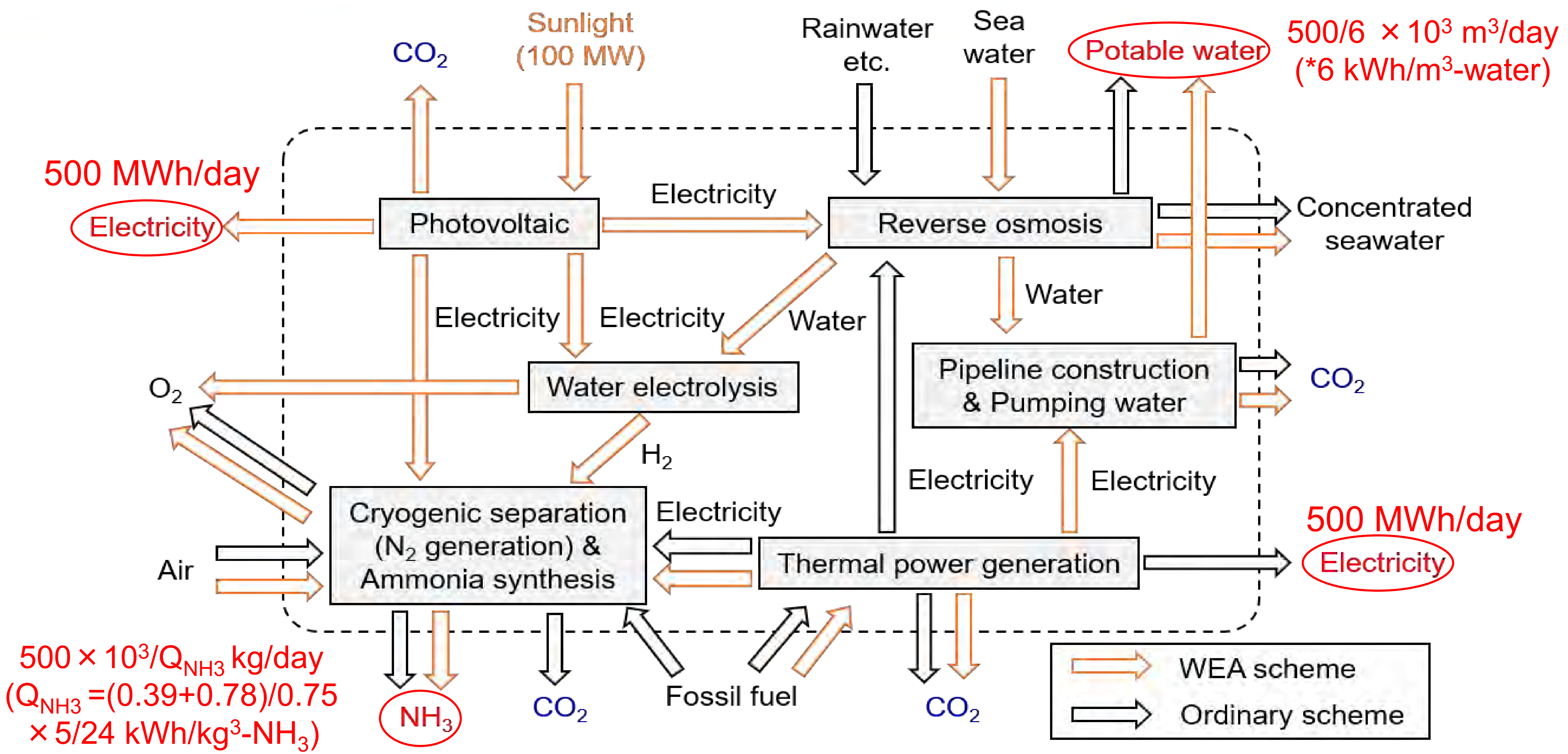
Thank you very much
for your time and attention.

Objectives

- Trade-off relation
  - Reduction of the CO_2 emission based on renewable energy
  - CO_2 emission from the pipeline construction & Transporting seawater
- The criteria to reduce CO_2 emission is not clear
  - **Distance** and **Elevation** from the sea to a city
- The evaluation of CO_2 emission as a function of **Distance** and **Elevation**
- WEA scheme: a base pattern
  - Photovoltaic & Reverse osmosis & Ammonia synthesis
  - Not reusing waste heat & reducing the total process number

System boundary

- Photovoltaic: 100MW
- Long term average of a potential PV electricity generation： 5 hours



*Ammonia synthesis process: Water electrolysis (H_2 generation), Cryogenic separation (N_2 generation), Synthesis loop ($N_2 + 3H_2 \rightarrow 2NH_3$)

Evaluation method

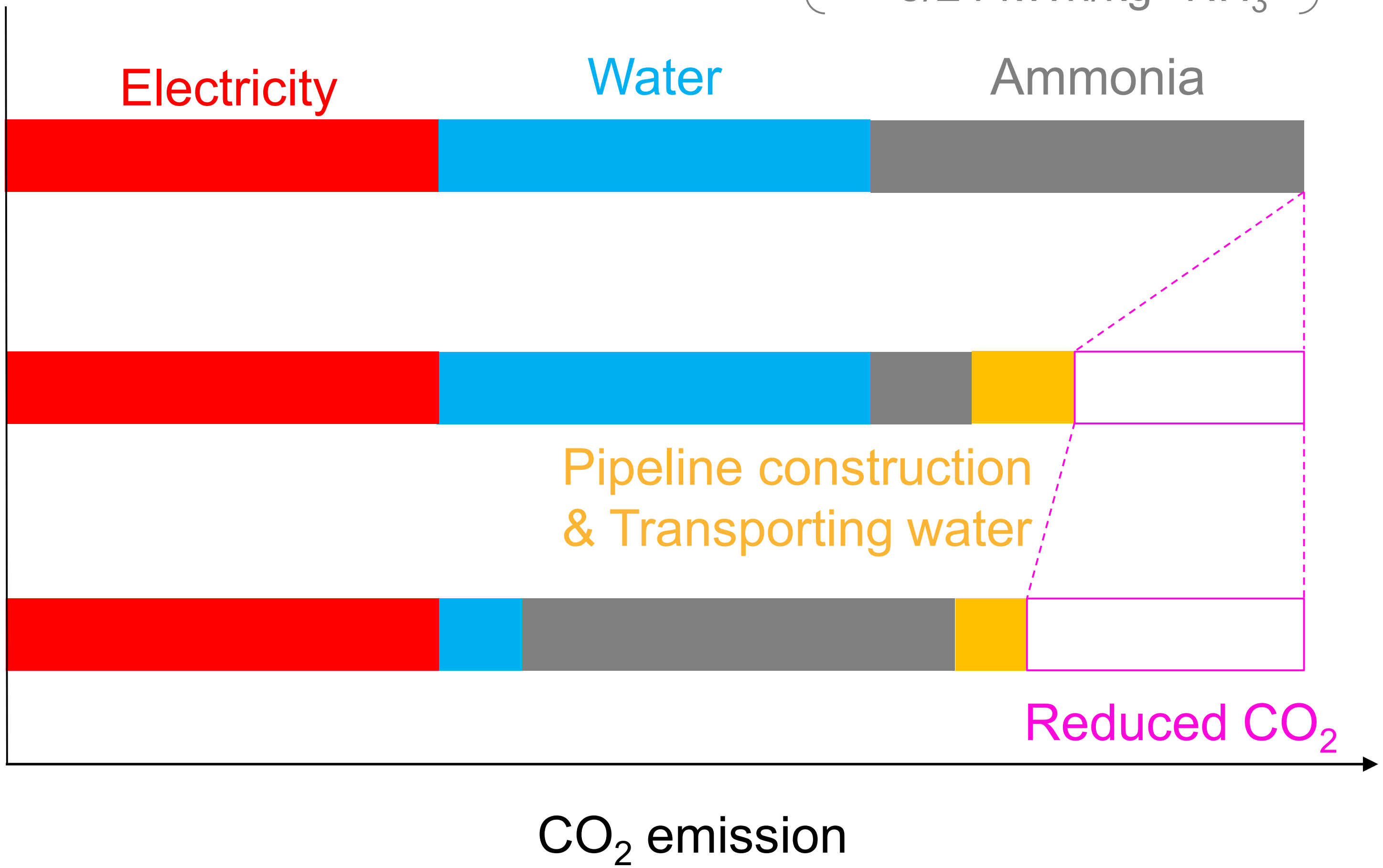
Functional unit = 500 MWh/day + 500/6 $\times 10^3$ m^3/day (*6 kWh/m^3-water) + 500 $\times 10^3/Q_{NH3}$ kg/day

Q_{NH3} =(0.39+0.78)/0.75 $\times$ 5/24 kWh/kg^3-NH_3

Water-Electricity-Ammonia were produced by conventional methods

Case 1: All electricity is consumed to Ammonia synthesis

Case 2: All electricity is consumed to Water desalination

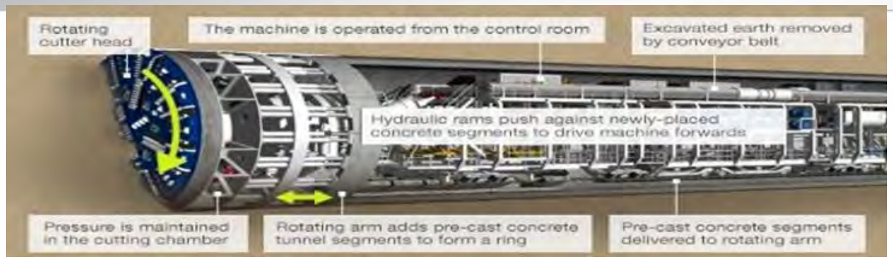


<u>Evaluation: Reduced CO_2 emission compared to conventional production</u>

Details of Evaluation assumption: Production

- Solar panel: Silicon type, 0.050 kg-CO_2/kWh[1]
- Reverse Osmosis : 6 kWh/m^3-water[2]
- Ammonia synthesis (conventional): 1.33 kg-CO_2/kg-NH_3[3]
- Ammonia synthesis (electricity based)
  - Efficiency for water electrolysis: 75%[4], Cryogenic N_2 separation:0.39 kWh/kg-NH_3 & Ammonia synthesis reaction: 0.78 kWh/kg-NH_3[5]
  - Ammonia synthesis reaction & Cryogenic N_2 separation requires constant operation because of their harsh reaction condition
  - For the two process, electricity based on fossil fuel is supplied for 19 hours (Electricity based on PV is supplied for 5 hours)
- Seawater is desalinated near to the sea & Brine water is disposed to the sea
  - Only desalinated water is transported
  - Water transportation is assisted by fossil fuel-based electricity
  - Electrical wires from a city to the sea is considered
- CO_2 emission factor for electricity[6]
  - Natural gas: 0.400 kg-CO_2/kWh, Gas/diesel oil: 0.700 kg-CO_2/kWh, Coking coal: 0.845 kg-CO_2/kWh

Details of Evaluation assumption: Pipeline



https://www.slideshare.net/RajarshiPaty/tunneling-ppt

- Pipeline construction
  - Material: Concrete, 313 kg-CO_2/m^3 [7]
  - Thickness: 1/12 of inner diameter[8]
  - Lifetime: 30 years[9]
  - Inner diameter: the minimum CO_2 when 100% of water desalination
- Energy of drilling for a pipeline E_t (kWh/m): Tunnel Boring Machine (TBM)

l (m): Distance between a city and the sea

*UCS = Uniaxial compressive strength

$$E_t = \frac{l}{3600}\left(\mathrm{F} + \frac{2\pi NT}{V}\right) \qquad \mathrm{V} = \frac{-0.0464x + 5.6221}{6000}x, where\ x = \mathrm{UCS}\ (115\ \mathrm{MPa})$$

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

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

N = 0.0328 (rps)

- Transmission loss[10]
  - Lifetime: 70 years
  - P = 100 × 10^3 W
  - φ = 420 kV
  - R = 0.0462 Ω/km
  - Converter efficiency: 95%
  - Transformer efficiency: 99.5%

$$L = 1000l\left[\frac{P}{\varphi}\right]^2 R$$

- Construction of electricity wires： 5.9 × 10^5 kg-CO_2/2km[10]

- Energy for water pumping E_w (kWh/day): Bernoulli's principle & Darcy-Weisbach Equation

Friction & Potential energy

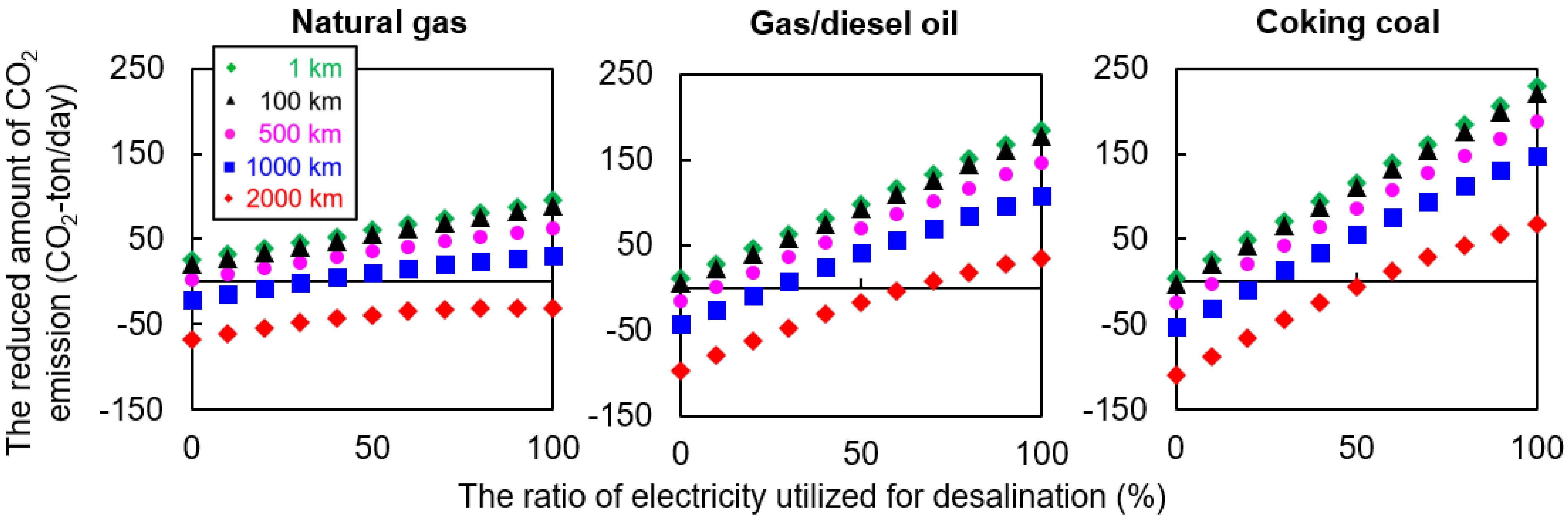
$$\mathrm{E}_w = \frac{24\mathrm{Q\rho g}}{1000\eta}\left(\mathrm{h} + \Delta\mathrm{z} + \frac{\Delta p}{\rho\mathrm{g}}\right) \qquad h = f\frac{l}{D}\frac{v^2}{2g} + (\zeta_e + \zeta_o)\frac{v^2}{2g} \qquad \mathrm{Re} = \frac{Dv}{\nu}$$

$$\mathrm{f} = \frac{64}{Re}\ (Re < 3000) \qquad \mathrm{f} = \frac{0.3164}{Re^{1/4}}\ (3000 < Re < 100000) \qquad \mathrm{f} = 0.0032 + 0.221Re^{-0.237}\ (100000 < Re < 3000000)$$

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

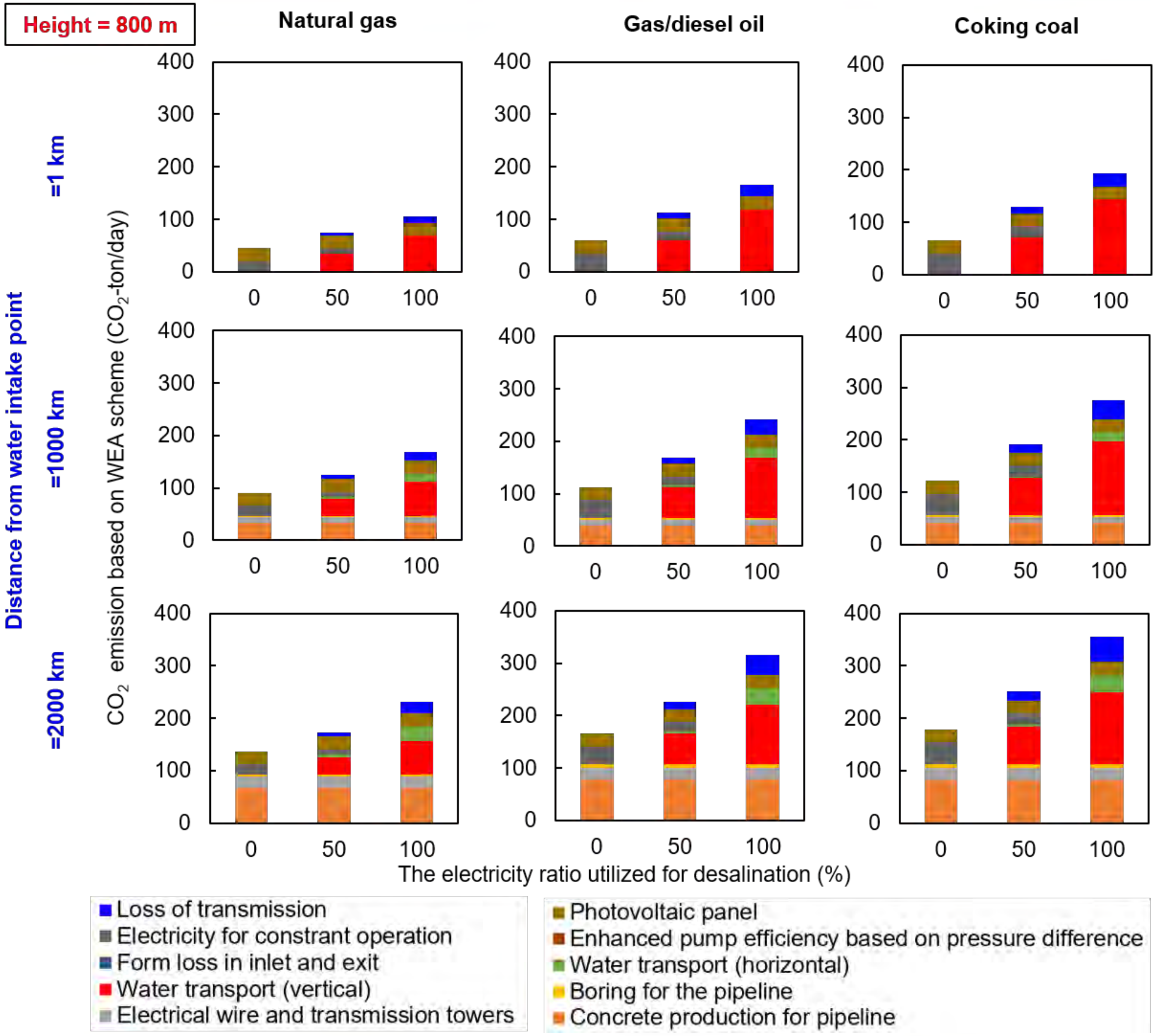
Fixed elevation: 800m (the world average)

- CO_2 emission factor for electricity[6]
  - Natural gas: 0.400 kg-CO_2/kWh, Gas/diesel oil: 0.700 kg-CO_2/kWh, Coking coal: 0.845 kg-CO_2/kWh



- PV electricity is supplied for "seawater desalination" or "ammonia synthesis"
- If the electricity is generated by 100% Natural gas, the city with the distance 2000km is cannot reduce CO_2 emission.
  - The longest distance from the sea (pole of inaccessibility): 2500 km[11]
- The cities closer to the sea can reduce CO_2 emission by increasing the ratio of water desalination.

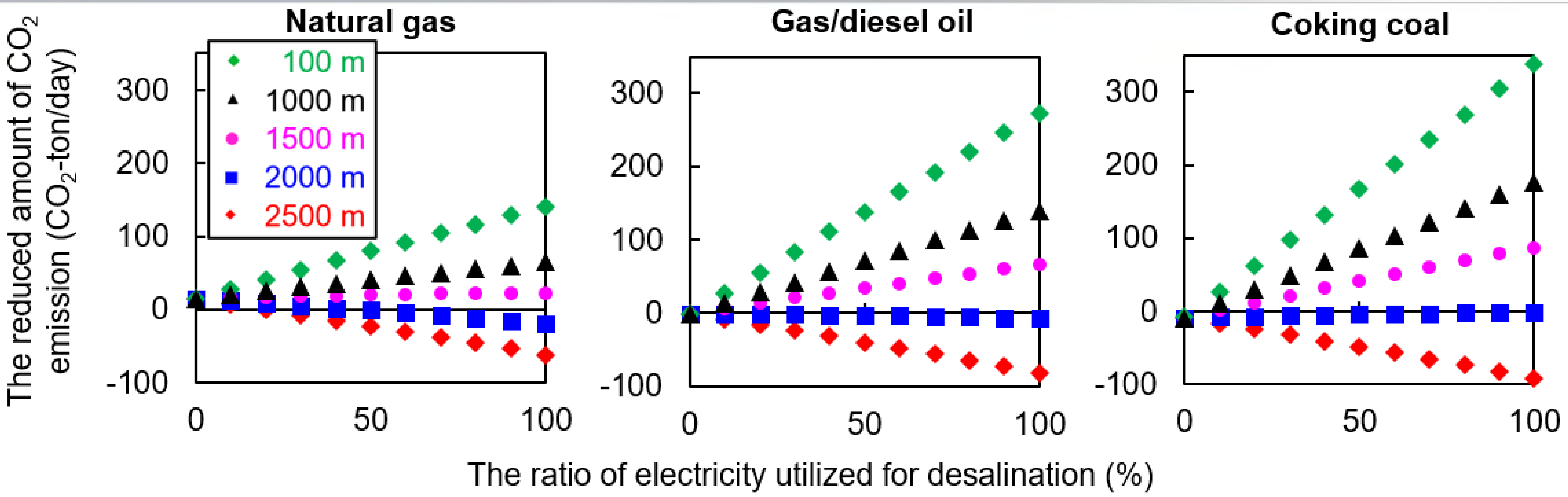
Fixed elevation: 800m (the world average)



Breakdown

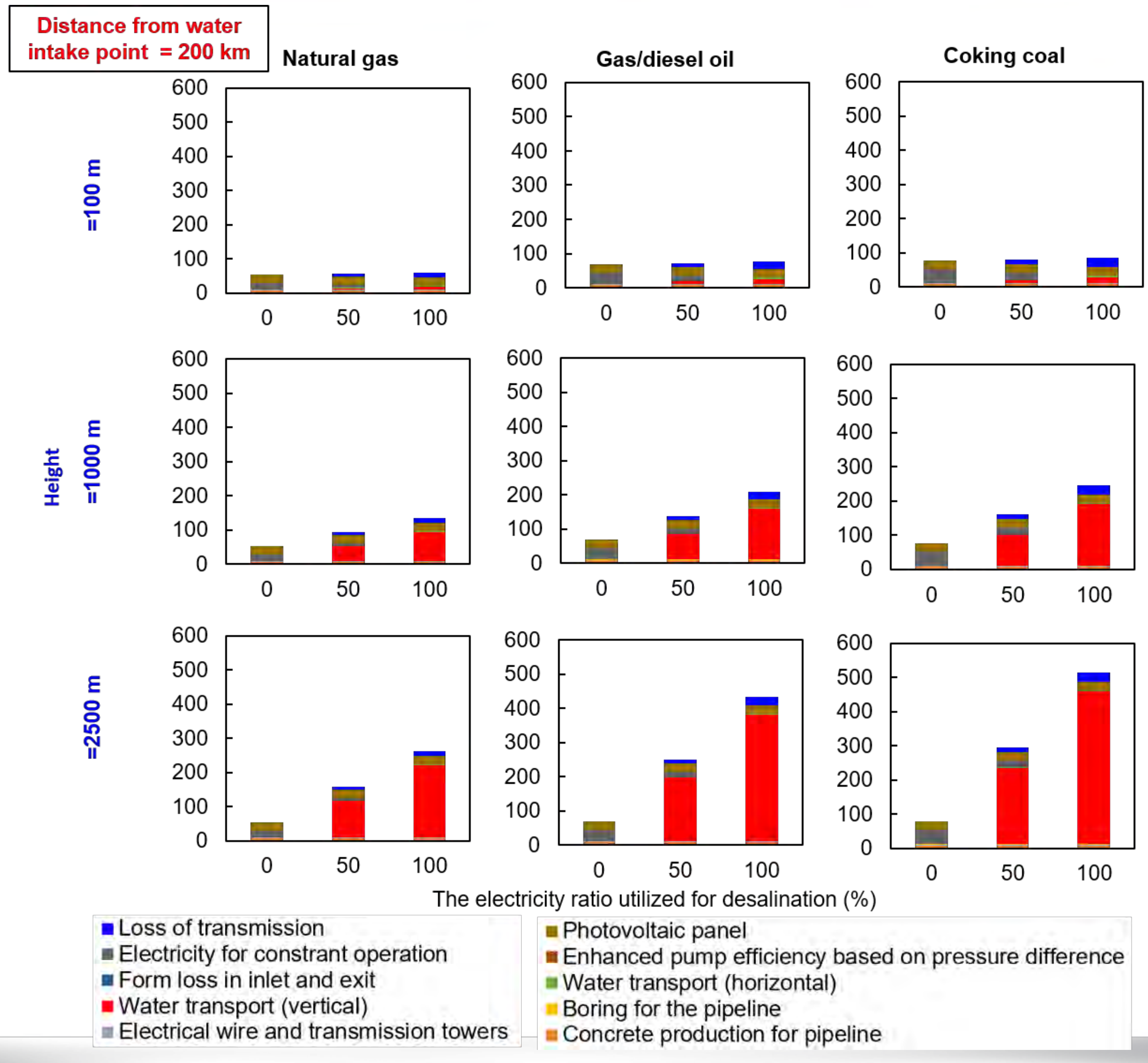
- In the case of 100% water desalination, the energy for pumping water (vertical direction) is the most dominant
- In case that the pipeline is very long (such as 1000 km), the concrete production is dominant
  - The longest pipeline of oil: 8707 km (West-East Gas Pipeline)
- The other parameters are not dominant

Fixed distance: 200km (Ref. Suez Canal = 193 km)



- Low elevation: Water desalination is better
- High elevation: Ammonia synthesis is better
  - Ammonia synthesis does not requires water so much
  - PV-based: 0.53 kg-CO_2/kg-NH_3 Conventional: 1.33 kg-CO_2/kg-NH_3
- If the elevation is around 2000m, the reduced CO_2 is zero or more than zero.
- The capitals in the high elevation: La paz in Bolivia (3500m), Quito in Ecuador (2850m), Mexico city in Mexico (2250m)

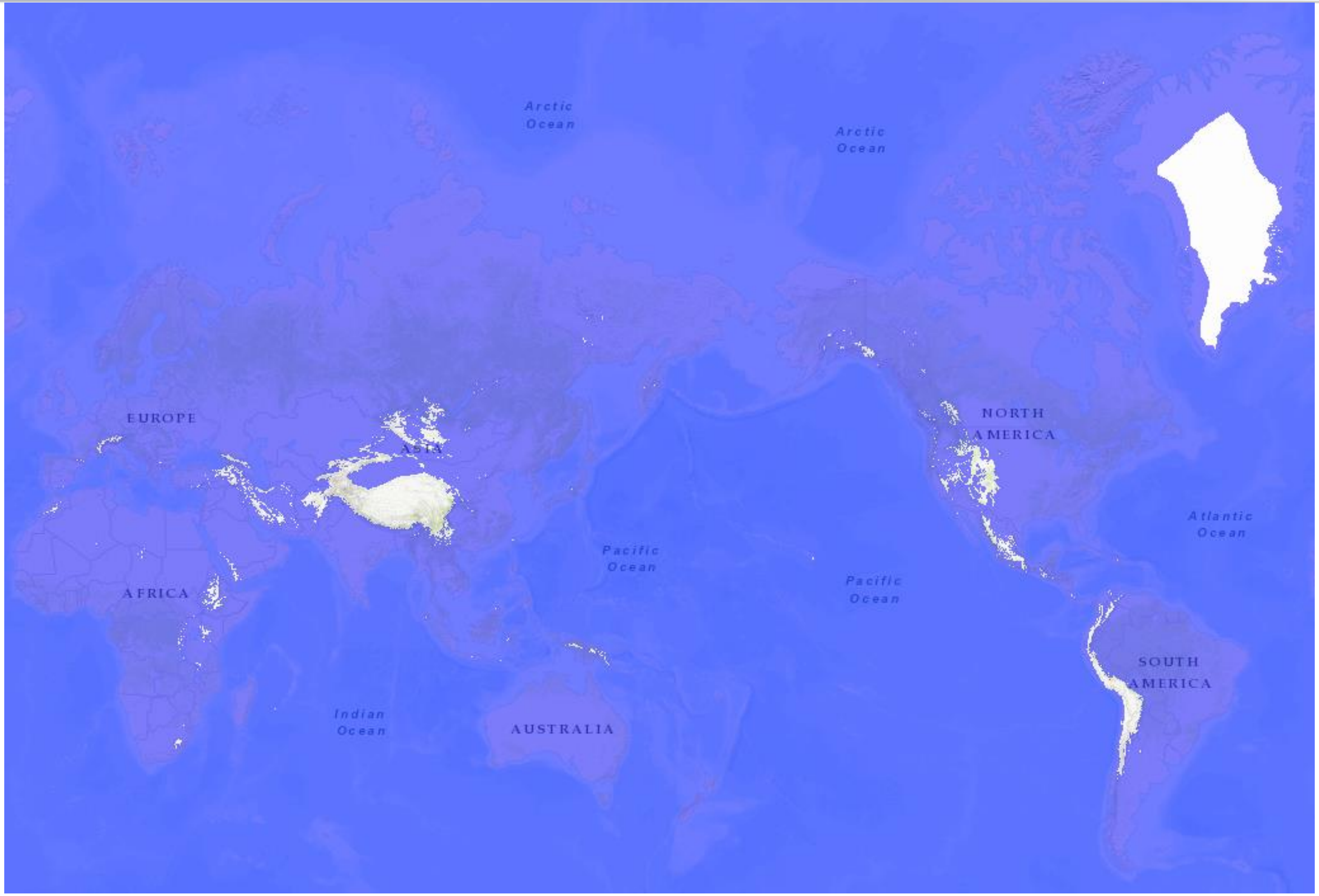
Fixed distance: 200km (Ref. Suez Canal = 193 km)



Breakdown

- In the case that the distance is close (within 200km), the dominant factor is the energy for pumping water (vertical direction)
- The other parameters are not dominant

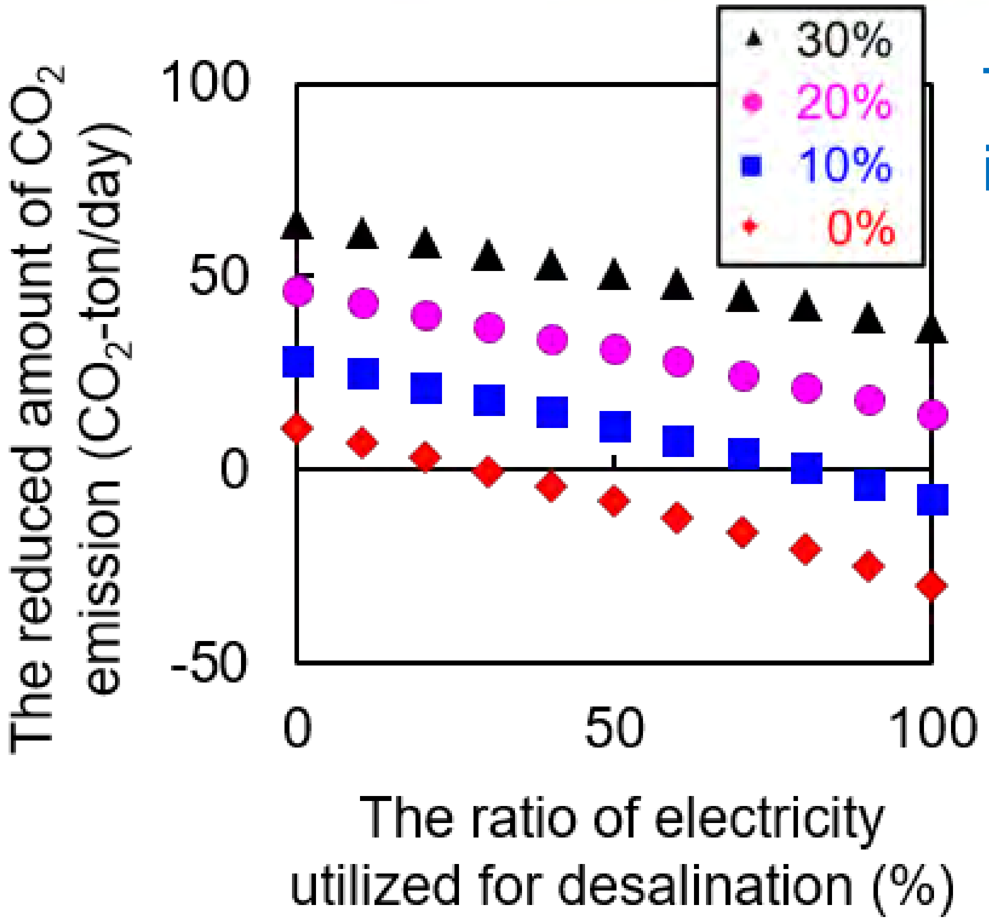
Elevation < 2000m



Flood Map: Elevation Map, Sea Level Rise Map, https://www.floodmap.net/.

- The region with “elevation < 2000m” is painted by blue
- Except for some (ex. Chile, Mexico), CO_2 emission can be reduced if the distance from the sea is within 200km

Mexico city (Distance: 250km, Elevation: 2250m)

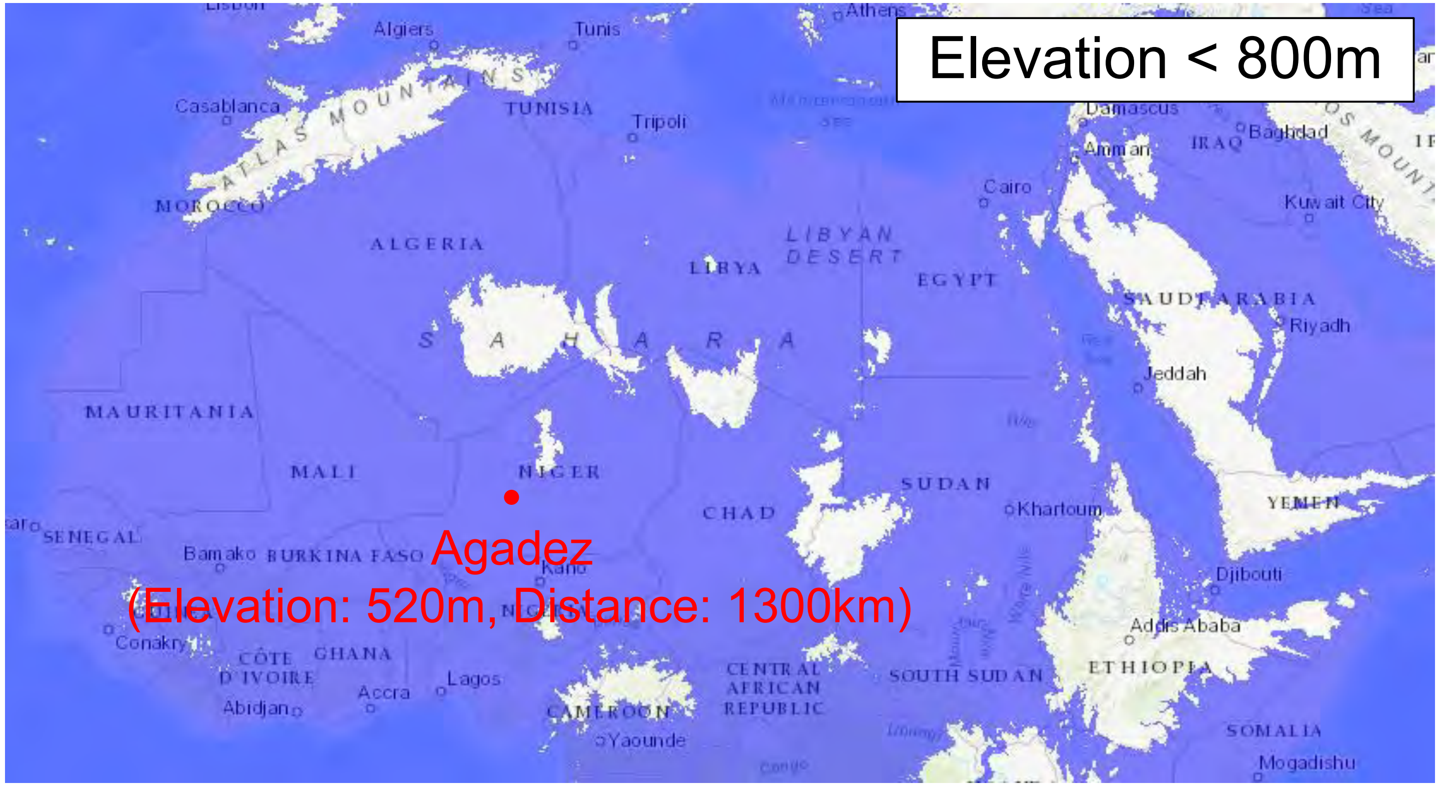


The ratio that PV electricity is supplied as electricity

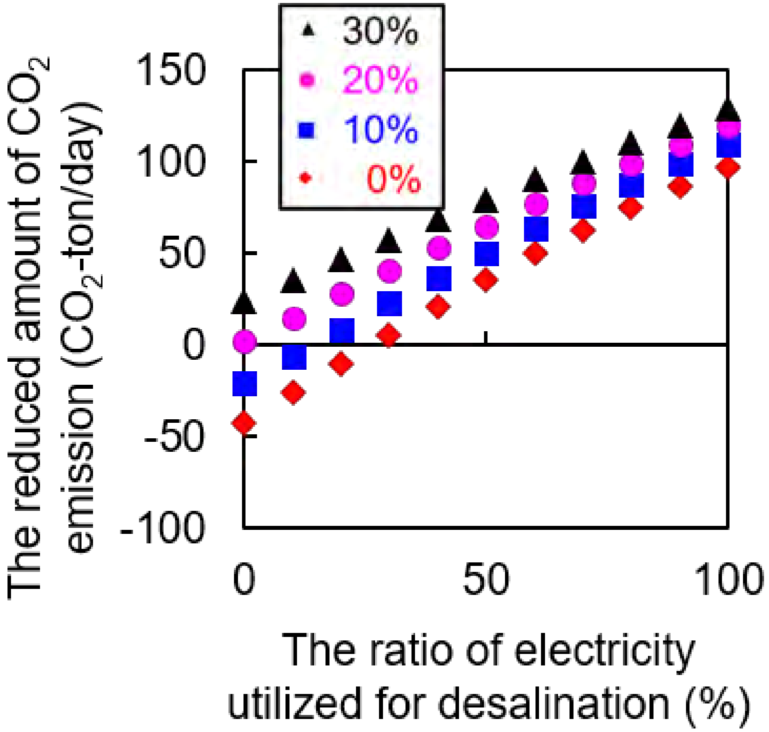
If the electricity generated by PV is supplied as electricity with more than 20%, even the case with 100% of water desalination can reduce CO_2 emission

The Sahara desert

Flood Map: Elevation Map, Sea Level Rise Map, https://www.floodmap.net/.



The ratio that PV electricity is supplied as electricity



Most of cities in the Sahara desert can reduce CO_2 by WEA scheme

Conclusion

- Pumping energy of water (vertical direction) is dominant in CO_2 emission
- Low elevation: Water desalination is better
- High elevation: Ammonia synthesis is better
- The cities within the distance of 200km from the sea can reduce CO_2
- The Sahara desert
  - The cities in the middle of the Africa continent can reduce CO_2
- Mexico city can reduce CO_2 if the electricity generated by PV is supplied as electricity with more than 20%
- Economic analysis will be the next research

Thank you very much for your time and attention.

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3. Bazzanella A and Ausfelder F., Low carbon energy and feedstock for the European chemical industry. 2017.
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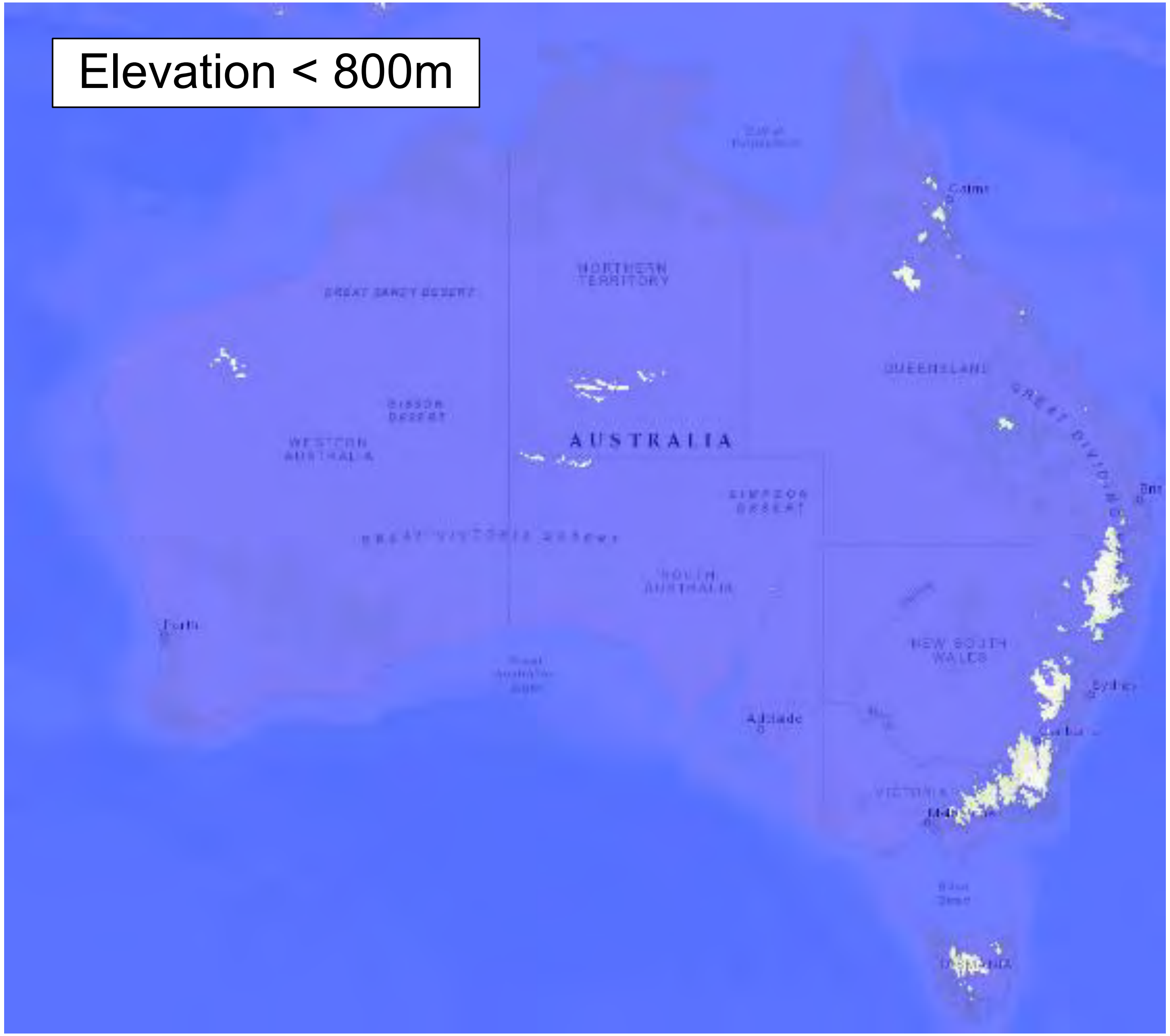
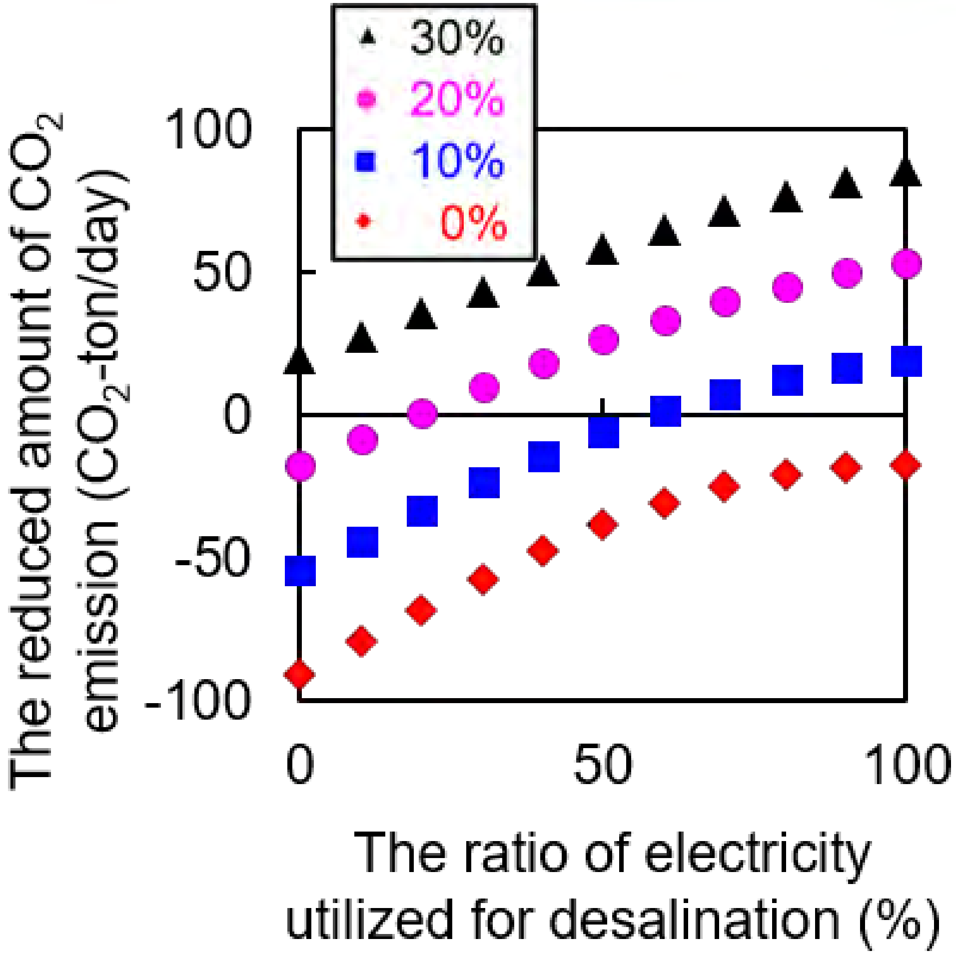
Australia



Flood Map: Elevation Map, Sea Level Rise Map, https://www.floodmap.net/.

Gobi desert



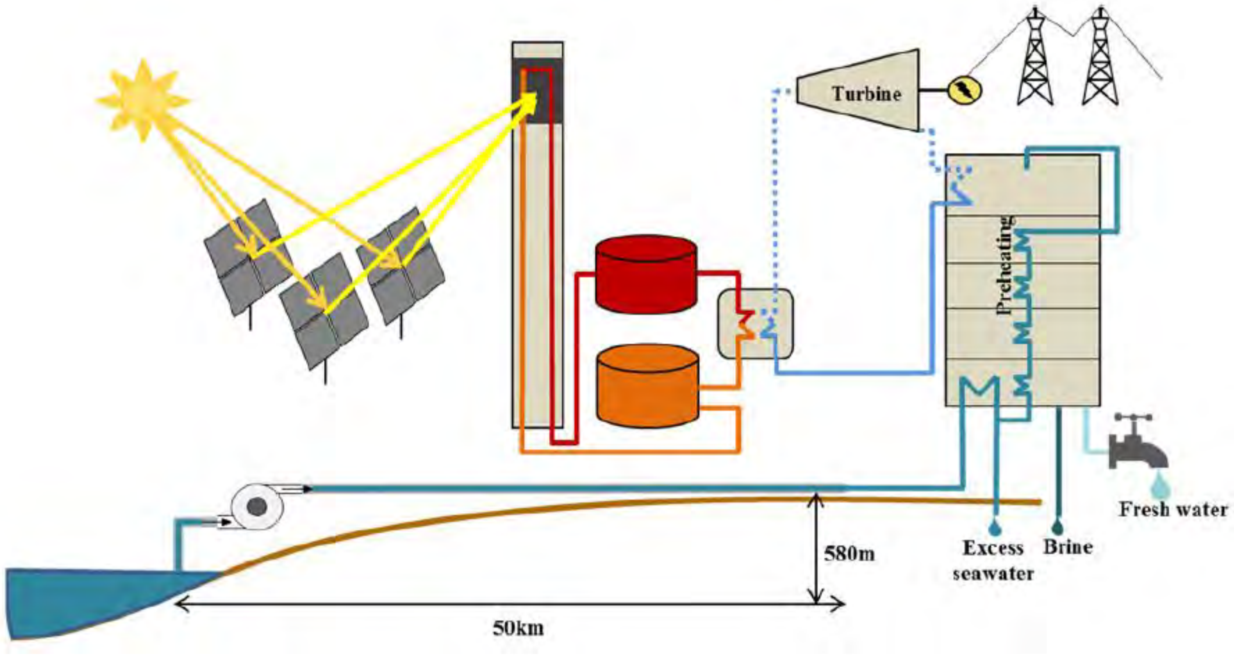
If the electricity generated by PV is supplied as electricity with more than 30%, all the case can reduce CO_2 emission

Blue: sea level = 0 m

Deserts under "sea level = 0 m"

Flood Map: Elevation Map, Sea Level Rise Map, https://www.floodmap.net/.

Why Jordan?

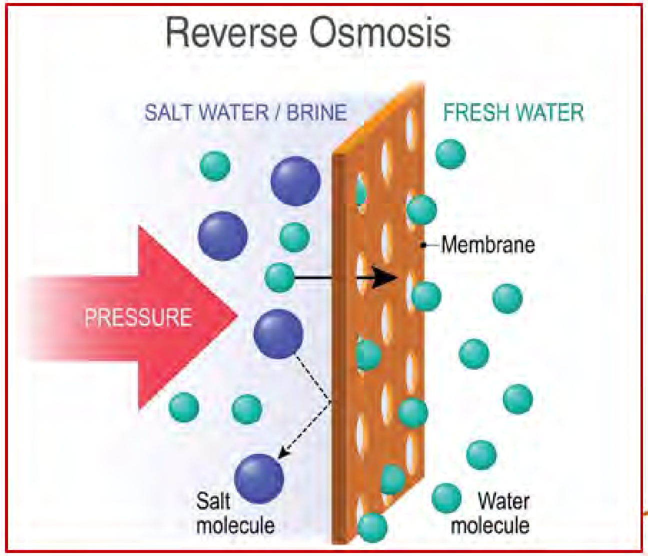


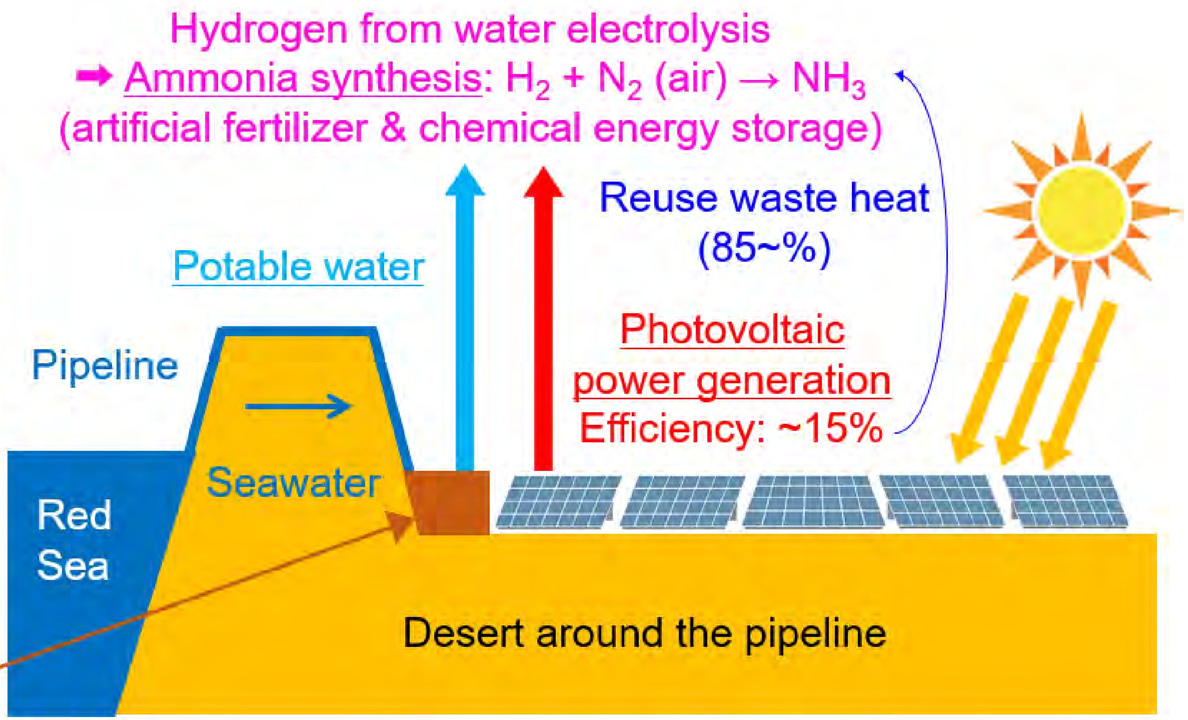
E. P. Dall and J. E. Hoffmann, AIP Conf. Proc. **1850** (1), 170002 (2017).

- Example of 100MWe CSP-desalination plant in Arandis, Namibia
  - Water and electricity are generated together without ammonia
- Bottleneck for economic feasibility is pumping seawater to desert.
- Pipeline for Red Sea-Dead Sea project will be very suitable

Scheme of WEA production (pattern B, C, D...)

https://www.watertechonline.com/metering-pumps-reverse-osmosis-water-treatment/





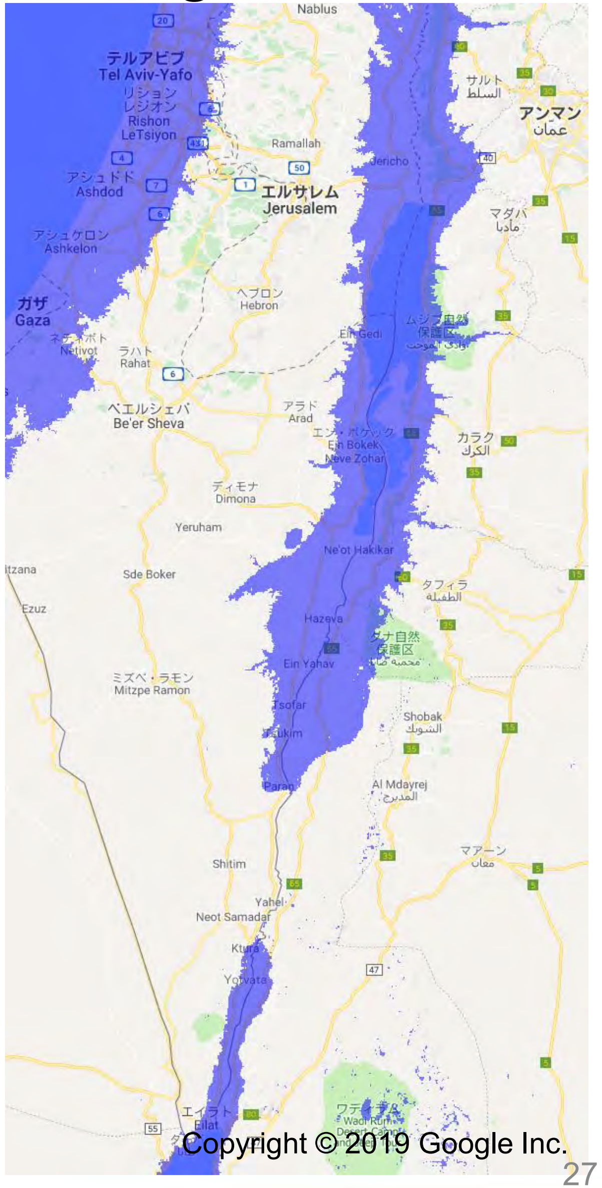
- Several patterns are possible
- As a first step, feasibility study based on simulation should be suitable

Simulation software:

Aspen Plus, Aspen HYSYS, Aspen Process Economic Analyzer

Potential of WEA scheme

- Firstly, the pipeline will pump up seawater to 125m in height
- Sunlight under the area at height 125m & south part of dead sea in Jordan
  - Total: 1.6 PWh/year
  - 7 % of world's electricity consumption (23 PWh/year @2018)
- Ammonia is a promising portable fuel
  - High energy density & liquid at 1 MPa
  - Energy for ammonia synthesis: 0.7 PWh/year
  - Market of ammonia: USD 49 billion in 2016
- Three main macronutrients are completed
  - Crops requires water, potassium (K), phosphorous (P), and nitrogen (N)
  - Jordan has abundant K and P
  - Ammonia and water will supply food production

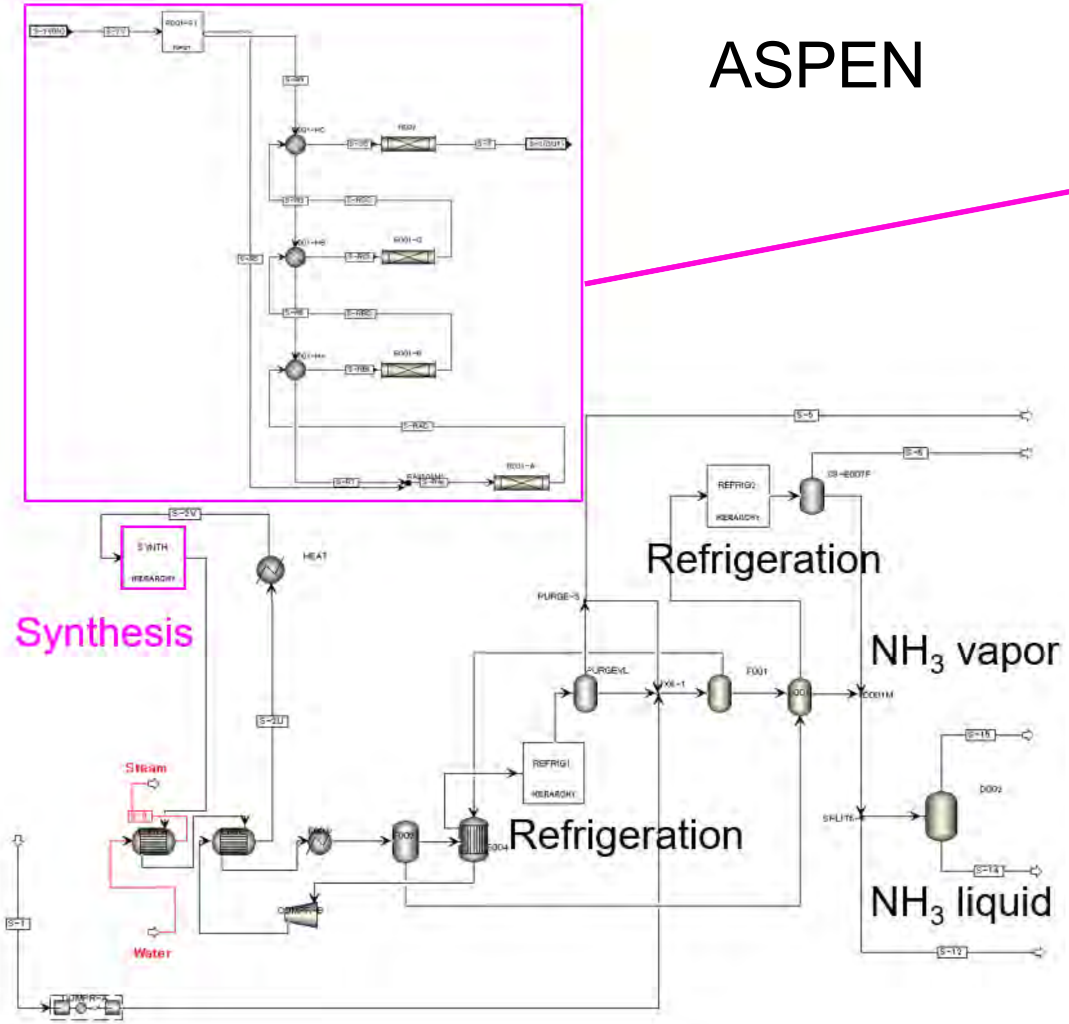


LCC evaluation

Ex.) Reactor in NH_3 synthesis

$$C_j = C_{j,fixed} + C_{j,ref}(\chi_j / \chi_{j,ref})^{\beta j}$$

ASPEN



Unit	Basis	$C_{j,fixed}$	$C_{j,ref}$	$\chi_{j,ref}$	β_j
Reactor	Volume, m^3	66,800	268,000	20	0.52

Assumption for water cost in 2040

Year	2017	2020	2030	2040
Running cost(MJD)	233	1081	1633	2346
Use (MCM)	1054	1677	2083	2353

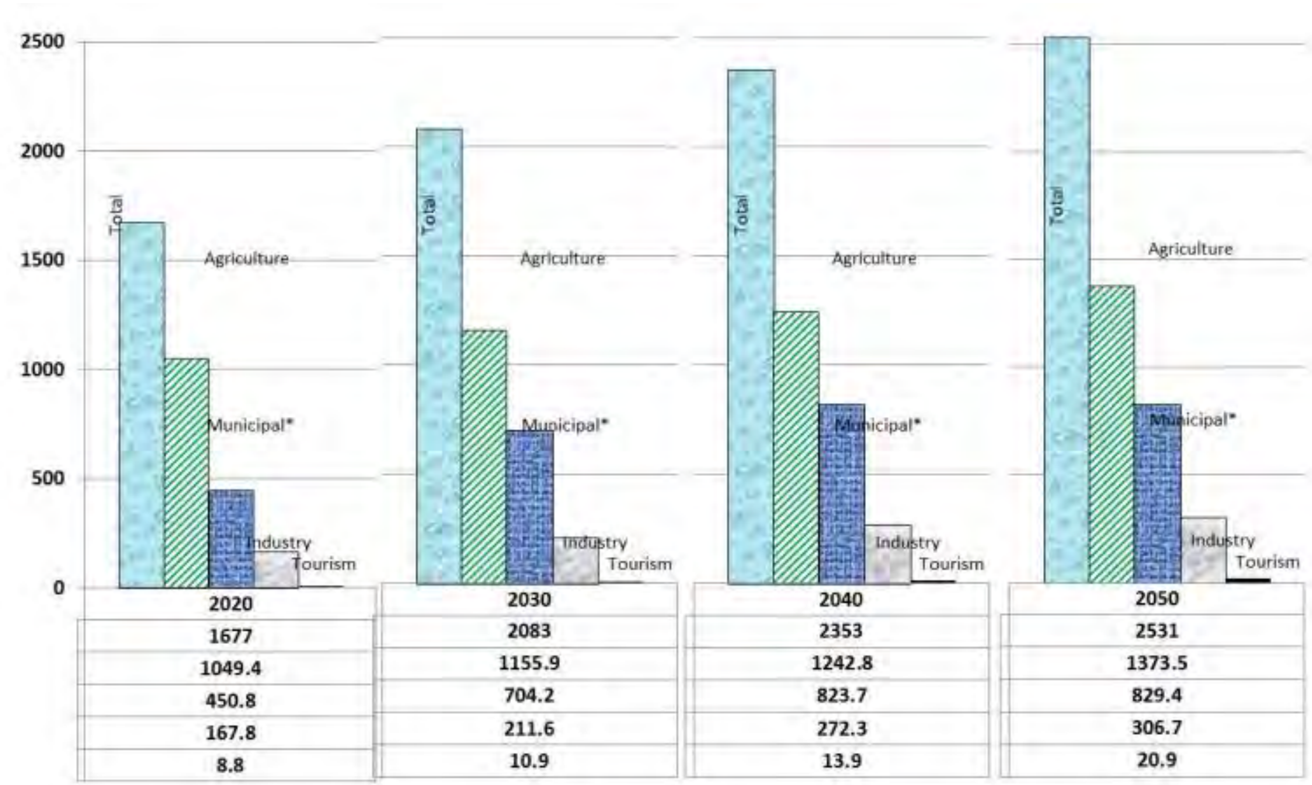
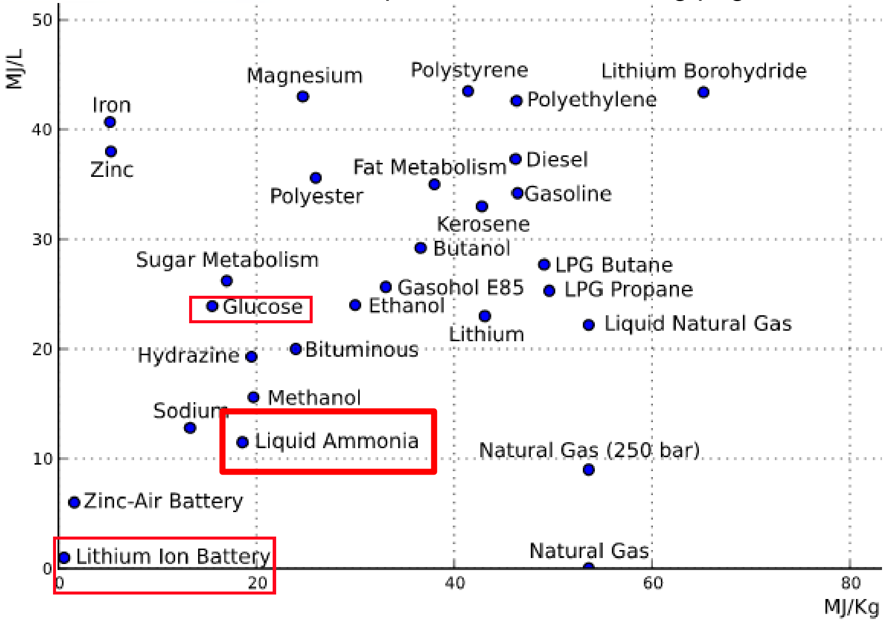


Figure 3: Future Water Demand (2020-2050)

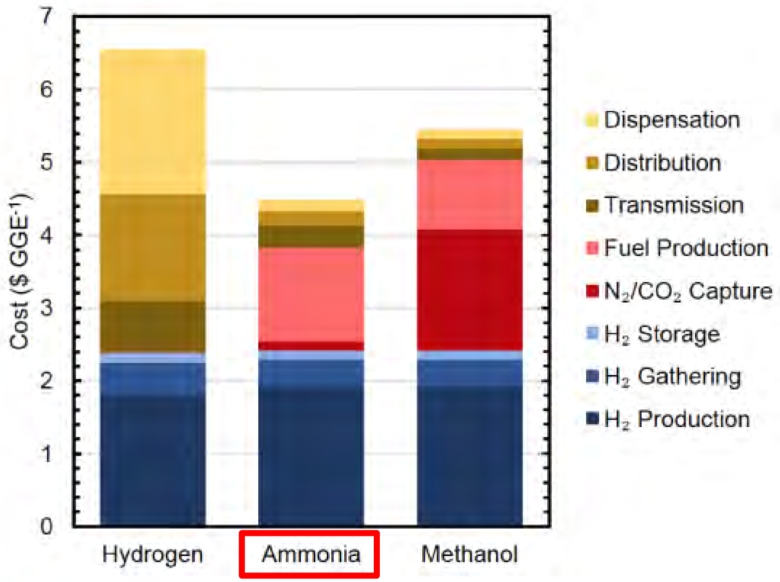
“Water Valuation Study: Disaggregated Economic Value of Water in Industry and Irrigated Agriculture in Jordan” U.S. Agency for International Development

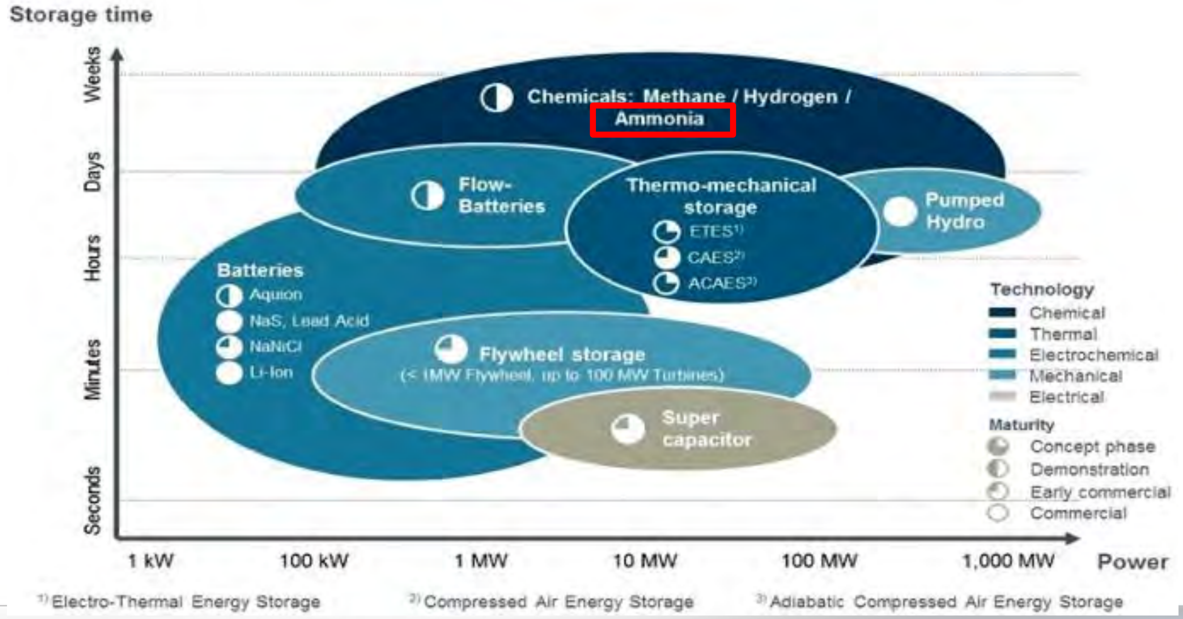
Promising property of ammonia as portable fuel

http://cafe.foundation/blog/page/70/



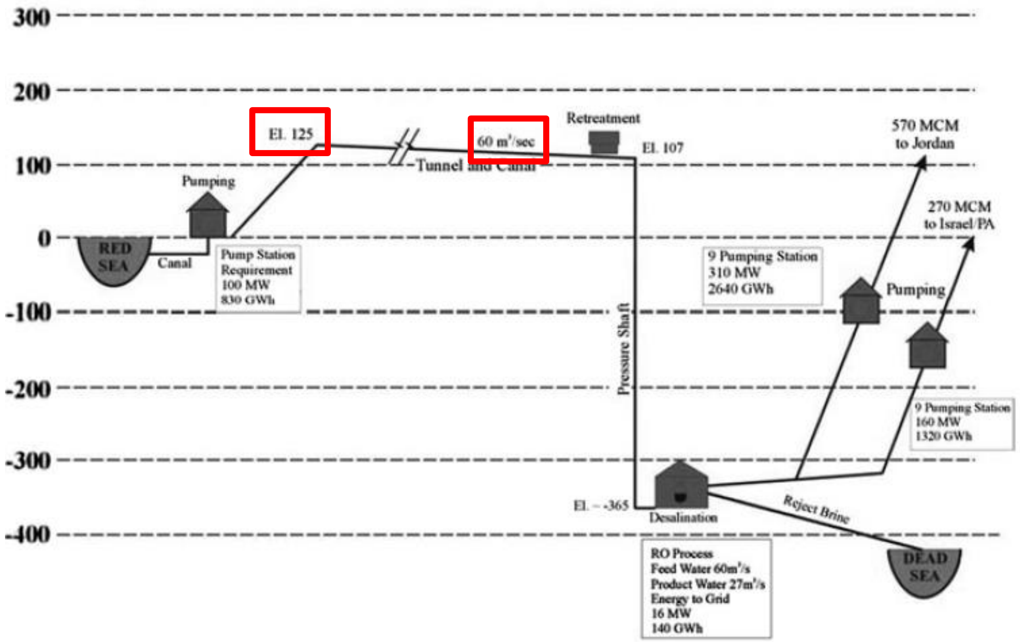
https://www.greencarcongress.com/2019/07/20190731-dafc.html





A. Valera-Medina, H. Xiao, M. Owen-Jones, W. I. F. David and P. J. Bowen, Progress in Energy and Combustion Science 69, 63-102 (2018).

Path of pipeline



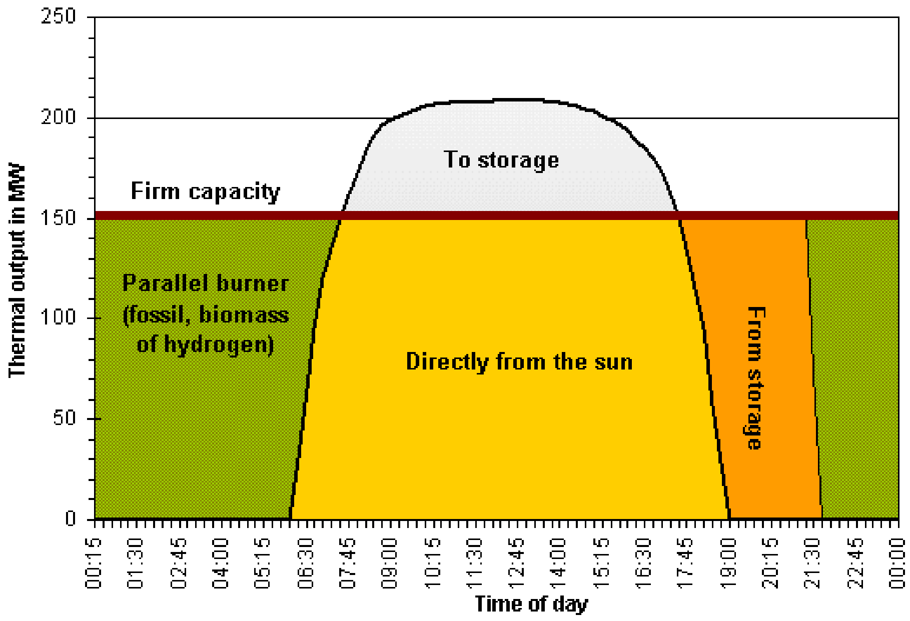
"The Red Sea–Dead Sea Canal: Its Origin and the Challenges it Faces", DOI: 10.1007/978-3-642-14779-1_5

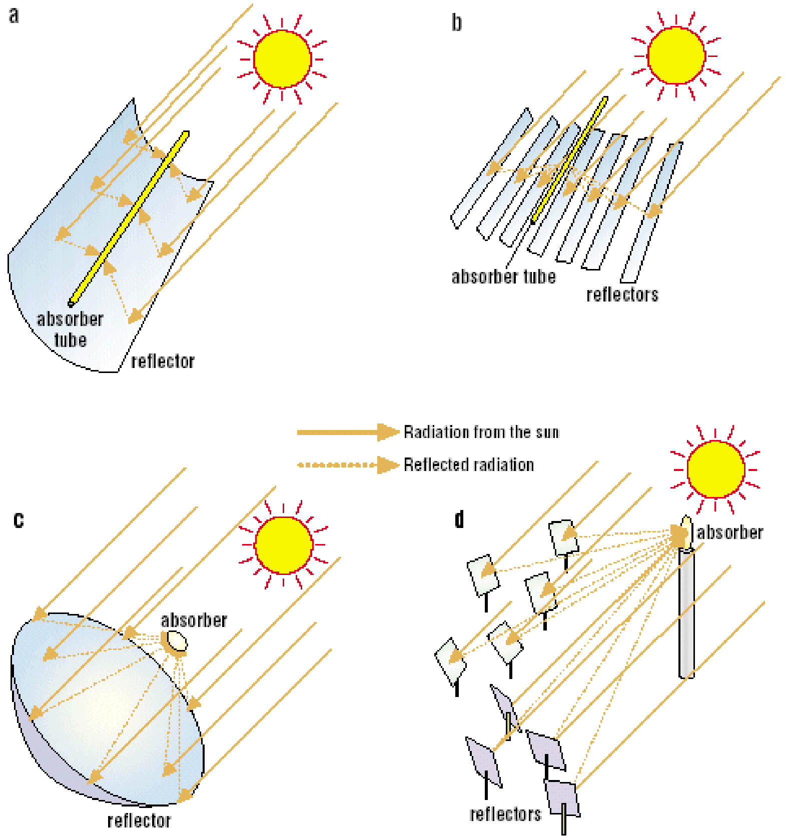
http://www.israelscienceinfo.com/en/environnement/canal-mer-morte-mer-rouge-les-travaux-vont-demarrer-en-2018/

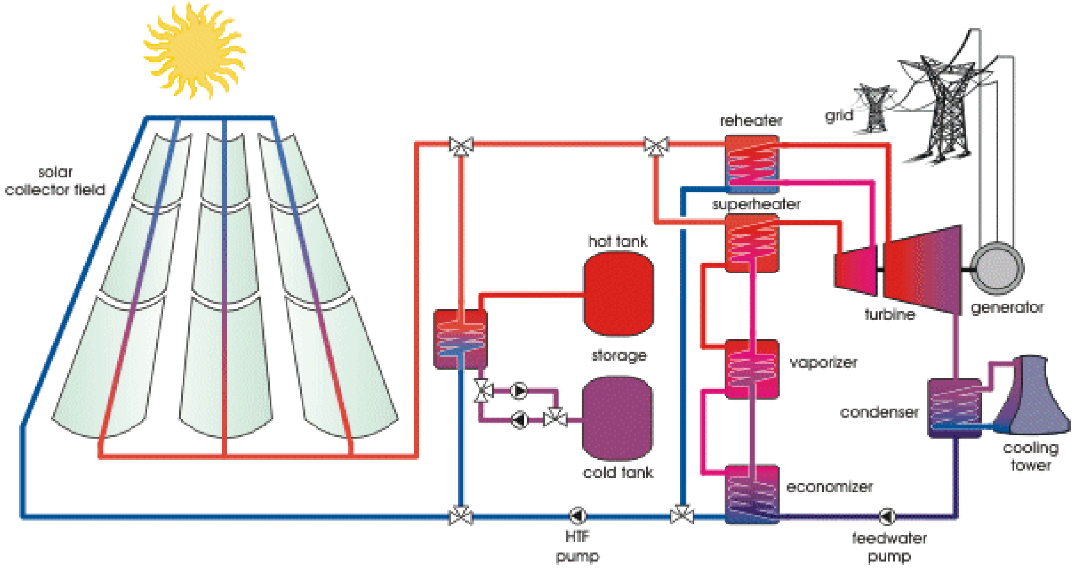
- Water amount: 1.9 x 10^{12} kg/year
- Sunlight in the south area of dead sea under 125 m (1.6 PWh/year) for latent heat and increasing temperature (25→400℃) of water: 1.4 x 10^{12} kg/year

→ Plenty of water to utilize sunlight

Solar thermal power generation





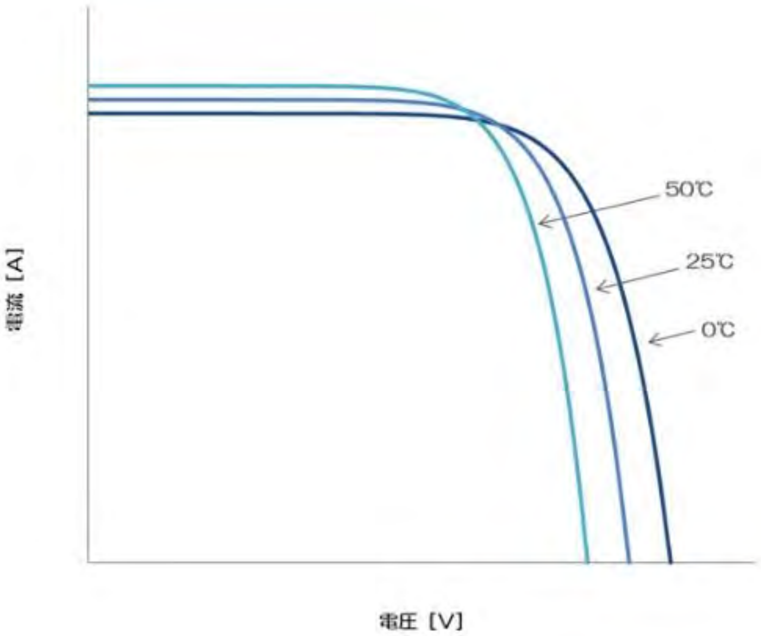


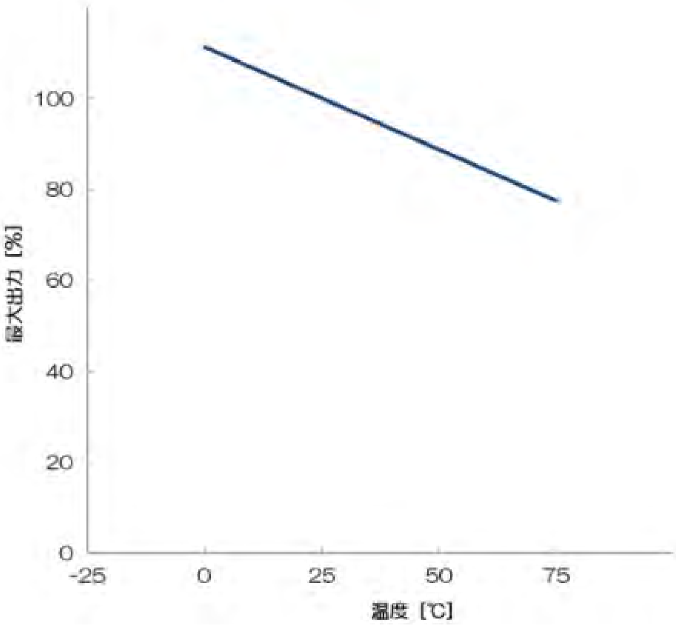
https://www.volker-quaschning.de/articles/fundamentals2/index.php

Decrease of PV efficiency

- 0.45% in efficiency is reduced as panel temperature increases 1 ℃
- 30 ℃ makes PV panel 70-80℃.

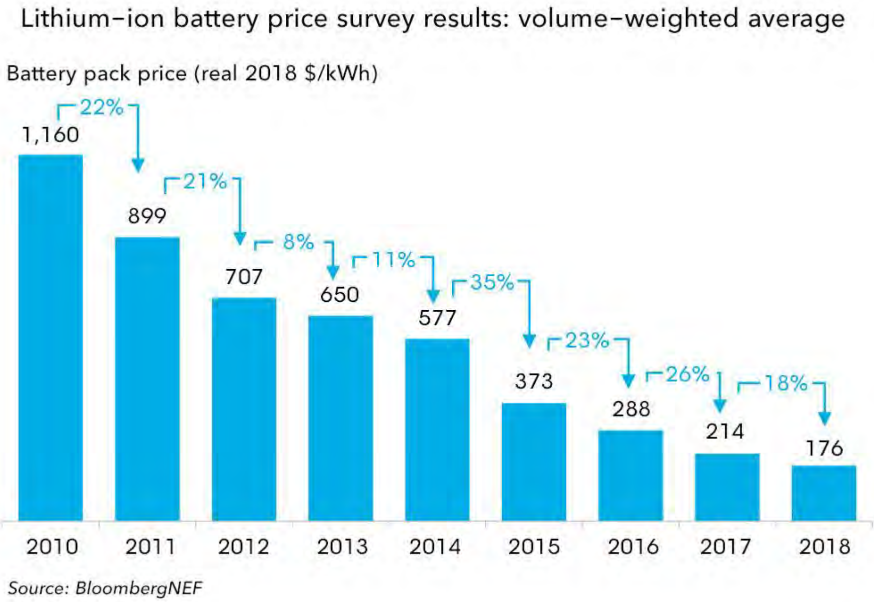
→ ca. 20% loss in efficiency

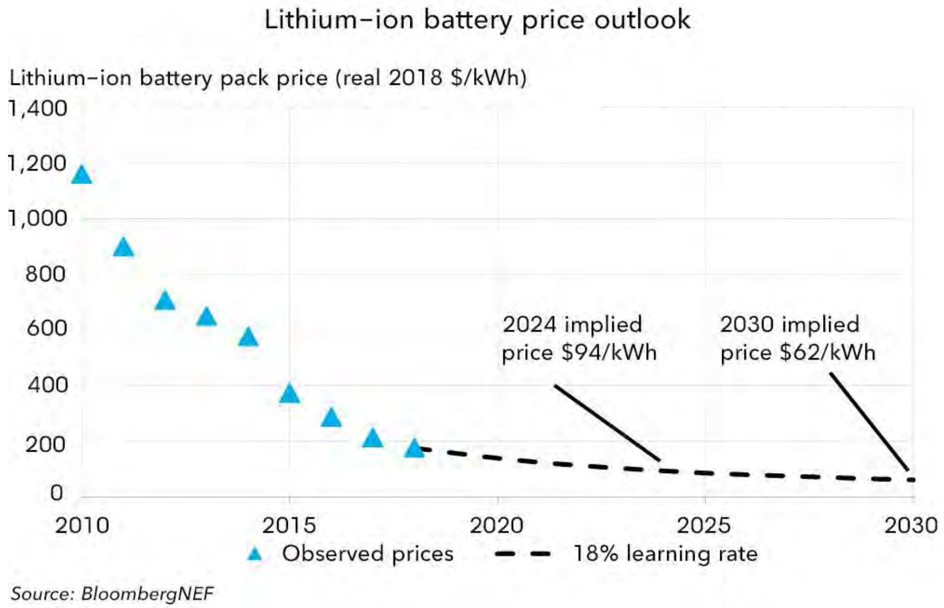




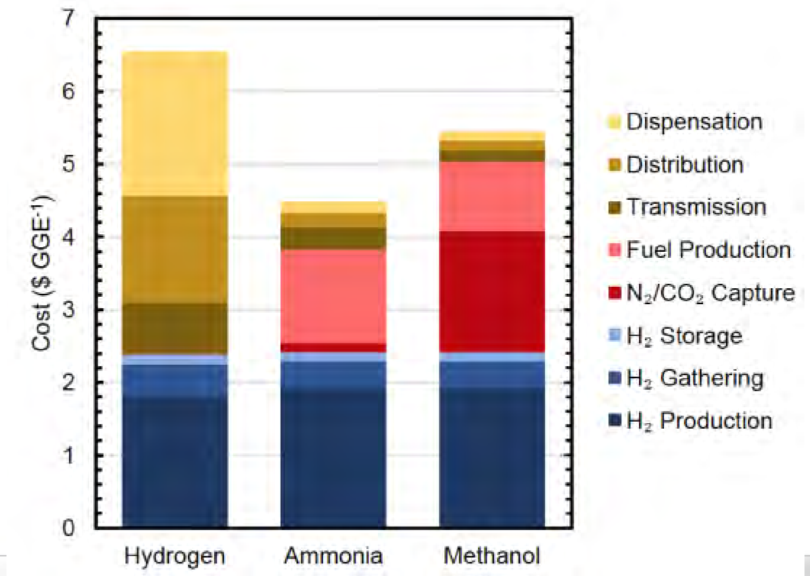
http://www.solartech.jp/module_char/temp_effect.html

Cost of storage for a car





https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/



GGE = Electricity kWh x 0.031

Ammonia: 0.1302 $/kWh

https://www.greencarcongress.com/2019/07/20190731-dafc.html

Direct ammonia fuel cell

Development of Solid Oxide Fuel Cell Systems for Utilization of Ammonia as Energy Carrier

Koichi Eguchi*

Graduate School of Engineering, Kyoto University, Nishikyo-ku, Kyoto 615-8510, JAPAN
eguchi@scl.kyoto-u.ac.jp

Among various hydrogen carries, ammonia is one of the promising candidates because of its high hydrogen density and boiling point and ease in liquefaction and transportation. The reaction temperature of ammonia cracking to nitrogen and hydrogen, being about 600˚C or higher, is close to the operating temperature of solid oxide fuel cells (SOFCs). A demonstration of the stack-level ammonia-fueled SOFC systems is an important step for the actual utilization of ammonia-fueled SOFCs. In this study, 200 W class and 1 kW class SOFC stacks were applied for ammonia fueled generation systems.

Catalysts for decomposition of ammonia has been developed. The activity of Ni/Y_2O_3 and SrO modified Ni/Y_2O_3 for ammonia cracking was sufficiently high for combination with SOFCs.

A catalyst based on Co-Ce-Zr composite oxide has been developed for autothermal ammonia cracking. Autothermal cracking of ammonia is characterized by fast start-up in the exothermic condition. The start-up time required from the initiation of electrical heating to the achievement of the steady state was 130 s.

Ammonia fueled SOFC stack systems were evaluated. The cell consisted of a Ni/ZrO_2-based fuel electrode, ZrO_2-based electrolyte, and perovskite-type oxide air

Ammonia-Fueled Gas Turbine Power Generation

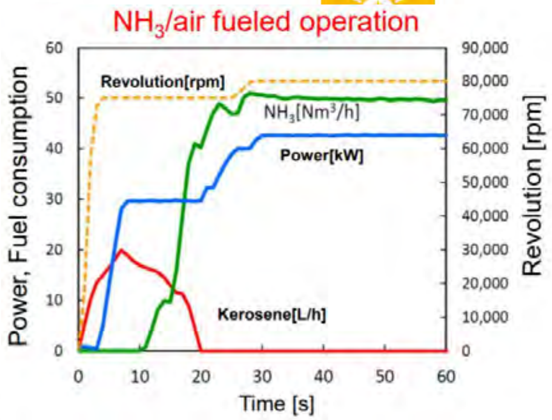
Power generation by combustion using ammonia

FY2019

Hideaki Kobayashi(Professor, Institute of Fluid Science, Tohoku University)

SIP

Energy Carrier "Ammonia Direct Combustion" Principal Investigator



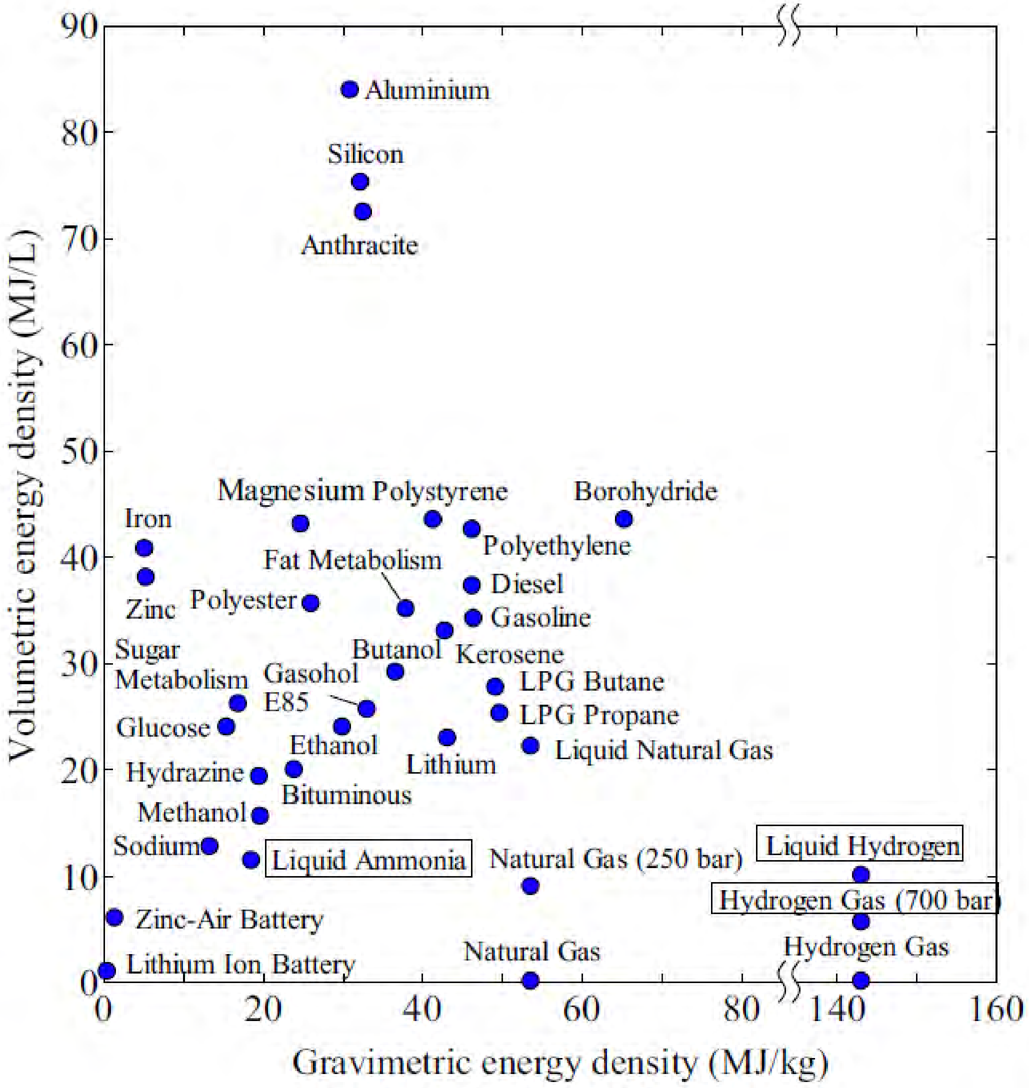
The world's first via gas turbine

Since ammonia does not emit carbon dioxide (CO_2) when burned, by replacing the coal and natural gas currently used as the fuel for power generation with ammonia, a large-scale reduction in CO_2 emission is anticipated. Traditionally, ammonia has been manufactured using fossil fuels as the raw material; however, in recent years, there have been attempts to manufacture ammonia using renewable energies such as solar power. If such a method can be put to practical use, ammonia could become a carbon-free fuel.

In "energy carrier," which is a topic in the "Cross-ministerial Strategic Innovation Promotion Program," (SIP) direct combustion of ammonia is one of the research and development areas. The research director, Professor Hideaki Kobayashi and his team members in AIST-FREA have developed the fundamental technology for direct combustion of ammonia, and achieved the world's first gas turbine power generation based on ammonia fuel in 2014. Furthermore, they succeeded in generating 2 MW large gas turbine power based on the fuel, in which 20% ammonia in lower heat value (LHV) is mixed in methane, in March 2018.

https://www.jst.go.jp/EN/achievements/research/bt111-112.html
http://injapan.no/wp-content/uploads/2017/02/13-Prof.-Kobayashi-Ammonia-Combustion.pdf

Energy density



H. Kobayashi, A. Hayakawa, K. D. Kunkuma A. Somarathne and Ekenechukwu C. Okafor, Proceedings of the Combustion Institute **37** (1), 109-133 (2019).