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Long-Distance Transport of Green Power via High Voltage Direct Current Submarine Cable

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Abstract. This study aims to perform a technical, environmental, and economic assessment of long-distance transport (around 10000 km) of green power from Australia to Japan through High Voltage Direct Current (HVDC) submarine power cables by literature studies. A PV power plant generates green power; 8000 GWh annual production is chosen as capacity. For the HVDC value chain, according to the assessments, energy efficiency is 74%. Power loss during cable transport is the key contributor. GHG footprint of power delivered is 112 kg CO2e/MWh compared to 50 kg at the outlet of the PV plant. Capital expenditure (CAPEX) is 29058 M€. At the end of the 10th and 20th years, another 4500 M€ investment is required for battery replacement. Operating expense (OPEX) is 166 M€/y. The technical cost of power produced is 428 €/MWh. Results of sensitivity analysis show that submarine cables length, power loss and lifetime, battery storage system sizing, and power plant availability have a significant impact on the economic and environmental performance of the whole HVDC value chain.

1 Introduction

As a consequence of the Paris Agreement, the global energy system must reduce its greenhouse gas (GHG) emissions. Energy generated from renewable sources will play an increasingly vital role as renewable energy can be supplied with low GHG emissions[1].

From a global point of view, the spatial offer of renewable energy such as solar power differs significantly due to regions of renewable energy surplus on the one hand and regions with high energy demands on the other. There are various ways of green power transport, either by cables or by chemical molecules, etc. High Voltage Direct Current (HVDC) transmission lines are one option for power transport[2].

The first submarine power HVDC cable used for electricity transmission was commissioned in 1954, connecting the electric grid of Gotland Island to Sweden's mainland grid. The cable was rated at 20 MW, traversing a submarine route length of 98 km[3]. Among existing submarine power transmission projects, NorNed Link has a 580 km length of submarine cables, the longest up-to-date power submarine cable. Among the planned submarine power cables in the world, two cables are longer than or equal to 1000 km: Ice Link (1170 km) and Euro-Asia Interconnector (1000 km)[4].

This study evaluates the efficiency and performance of transporting 1 GW of green power generated by PV plant via HVDC submarine cable with the reference case of Australia - Japan. It includes a general description of the HVDC value chain (from power production to grid in the end-user country), technical assessments of each process involved in the value chain, and environmental and economic performance, as well as energy efficiency in order to provide a state-of-art of HVDC application in long-distance power transport and support further R&D development/business case reflection.

2 Methodology

2.1 Technical assessment

When using submarine HVDC cable to transport electricity from Australia to Japan, the whole value chain can be divided into five sections, which is showed in Fig. 1, including renewable power generation, equipped with energy storage system (ESS) to ensure 1 GW stable power (Australia), converter station (Australia), subsea transmission (between Australia and Japan), converter station (Japan) and AC grid (Japan).

Fig. 1. Simplified Block Flow Diagram of HVDC chain between Australia to Japan.

2.1.1 Green power production

In 2020, 27.7% of electricity was generated from renewable energy in Australia. Solar energy accounts for 34.4%, which is the main contributor to renewable

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generation[5]. Hence, a PV plant in New South Wales (NSW), the eastern part of Australia, combined with an energy storage system, is assumed to provide 8000 GWh power per year (with an average power production of 1 GW and 8000 hours as max operational hours).

Availability of PV is one key parameter that reflects its intermittency, which can be defined below. Considering the location of the PV plant, 27% availability is chosen[6], which can be used to obtain the installed capacity of the PV plant, 3.7 GW.

2.1.2 Energy storage system

Lithium-ion battery technology is relatively mature and has a high energy density, and is considered one of the most promising battery storage approaches, which is chosen as the energy storage system in our base case, assuming an efficiency of 90%[7]. Several batteries are connected in parallel to meet the required storage capacity. The energy storage system should allow storing the difference between the power produced by the power plant and average power output.

In our study, by simplification, we assume an optimist case as base case: battery full charge phase and use phase can be finished in a single day. Averaging charging hours per day of renewable power plants are simplified as average full load hours of power plants per day. Hence, the average full load hours and averaging charging hours for the PV plant are 2365 hours per year and 6.5 hours/day, respectively. After considering the efficiency of batteries, the installed capacity of battery installed capacity can be calculated by equation (1).

$$C_{EES} = (P_{EES} * T_{charing})/\eta_{EES} \qquad (1)$$

Where $C_{EES}$is the installed capacity of energy storage system (GWh), P_{EES} is the power of energy storage system (GW), is the charging hours of energy storage system (hours/day), is the efficiency of energy storage system (%). Key assumption of the installed capacity of PV plant and energy storage system is shown in Table 1.

Table 1. Key assumptions of installed capacity of PV plant and energy storage system.

Key assumptions	Value	Unit
Power generation of PV plant	8000	GWh
Installed capacity of PV plant	3.7	GW
Power of energy storage system	2.7	GW
Installed capacity of energy storage system	19	GWh

2.1.3 Converter station

There are two converter stations in the HVDC value chain: one is between the PV plant and submarine cable (located in Australia), and the other is between submarine cable and AC grid (located in Japan).

For the converter station in Australia, the primary function is to convert low voltage into high voltage. It is worth mentioning that, for a PV plant, a DC/DC converter is required (as PV produces DC power). For the converter station in Japan, its function is to convert DC into AC and high voltage into low voltage. In our study, we choose Voltage Source Converter (VSC) as converter technology because it is newer and more flexible than the traditional technology of Line Commutate Converter (LCC)[8].

There are three key parameters for a converter station: power loss, rated power, and voltage. 1% of power losses is considered in the current study[8]. The rated power of the converter is set as 1000 MW, based on the design of the power production and battery storage blocks. 320 kV is chosen as its output voltage[9]. The annual operating hours of converter stations are assumed as 8760 hours. Key assumptions of converter stations are listed in Table 2.

Table 2. Key assumptions of converter stations.

Key assumptions	Value	Unit
Converter technology	VSC	
Converter rated power	1000	MW
Converter voltage	320	kV
Converter power loss	1	%
Annual operating hours	8760	hours

2.1.4 Subsea transmission

Commonly used topologies of HVDC transmission systems are DC monopoles and bipoles. Considering the high reliability and large market share of the HVDC configuration, a bipolar configuration is chosen in our base case[8].

As one of the extruded cables, cross-linked polyethylene cable (XLPE) is chosen in our base case, which developed rapidly in the past 20 years due to the benefit of VSC technology's increasing market share[8].

Cable arrangement is related to the installation of submarine cables. In our study, the cable’s layout of two single-core cables bundled is chosen[4]. It requires only one trench to lay out 2 submarine cables, which is benefited to cost reduction.

320 kV of cable voltage and 500 MW power rating are assumed for each submarine cable[4]. The cross-sectional area of submarine cable with a rated power of 500 MW is about 630 mm2[10].

Most existing transmission power cables are laid in relatively shallow water, i.e., at less than 500 m depth. The deepest cables are installed around 1500 m[11]. The water depth from Australia to Japan is around 4000-6000 m. Since there is no submarine power cable installed in such a water depth, one limit of the current project is the maturity of deepwater installation.

There is no existing submarine power cable project with such a long distance between Australia and Japan, but many submarine optical fiber cable projects, such as AJC network (12700 km) and JGA Cable system (9700 km)[12, 13], globally have achieved lots of long-distance telecommunication transmission between Australia and Japan, which indirectly increase the feasibility of long-distance power transmission through HVDC submarine cables, especially in terms of water depth and transmission distance. In the current study, 9700 km is estimated as the length of submarine cables.

Cable joint is necessary, but its impact on cost and environmental performance is neglected in the current study[4].

Based on literature data, the subsea transmission power losses range is roughly 1.6-3.5%/1000 km[6, 14]. In our base case, 2.5%/1000 km is assumed as the power losses of submarine cables. Key assumptions of subsea transmission are presented in Table 3.

Table 3. Key assumptions of subsea transmission.

Key assumptions	Value	mm
Submarine cable configuration	Bipole	
Submarine cable type	XLPE	
Submarine cable power rating	500	MW
Submarine cable numbers	2	
Submarine cable voltage	320	kV
Cable conductor cross section	630	mm^2
Submarine cable arrangement	Two single-core cables bundled	
Submarine cable length	9700	km
Water depth	4000-6000	m
Cable joint	Required	
Subsea transmission power losses	2.5	%/1000 km
Annual operating hours	8760	hours
Submarine cable lifetime	30	years

2.1.5 AC grid

After HVDC submarine cable transmission, green power generated by renewable energy in Australia will be connected to the AC grid in Japan and then be supplied to users through a power distribution system. The impact of power import on the Japanese's grid is excluded in the current study.

2.1.6 Energy efficiency

Energy efficiency is defined as the ratio between the power input of the AC grid and the power output of the PV plant, which is expressed by equation (2).

$$\eta_{HVDC} = \frac{P_{in_{(AC\ grid)}}}{P_{out_{(PV)}}} \quad (2)$$

Where η_{HVDC} is the energy efficiency of the HVDC chain (%), is the power input of the AC grid (GW) and is the power input of the PV plant (GW).

2.2 Environmental assessment

For environmental assessment, we focus mainly on the greenhouse gas (GHG) emissions, with the terms of carbon dioxide equivalent (CO2e). A complete assessment or a focus on the marine ecosystem can be carried out as a separate study in the future.

GHG emissions can be divided into direct GHG emission (emitted during operation) and indirect GHG emission (related to construction). It is the sum of contributions from each block. For the PV plant, the GHG footprint has the range of 1-218 kg CO2/MWh with a mean of 49.91 kg CO2/MWh, and here it is expressed as 50 kg CO2e/MWh produced[15]. This value already takes into account plant availability and lifetime. The annual GHG emission of the PV plant can be calculated by equation (3).

$$GHG_{PV} = E_{output} * GHG_{PV} \quad (3)$$

Where is the GHG emission of PV plant (kg CO2e), is the annual energy output of PV plant (MWh), is the GHG footprint of PV plant (kg CO2e/MWh).

For the lithium-ion battery storage system, available data from the literature review is in the range of 40-110 kg CO2e/kWh installed[16]. We take the median value of 75 kg CO2e per kWh installed capacity as the base case. Hence, the annual GHG emission of the energy storage system can be calculated by equation (4).

$$GHG_{EES} = (C_{EES} * GHG_{unit})/T \quad (4)$$

Where is the GHG emission of energy storage system (kg CO2e/year), is the installed capacity of energy storage system (MWh), is the GHG footprint per installed capacity of energy storage system (kg CO2e/MWh), and T is the lifetime of energy storage system (year).

The GHG emissions of submarine cables come mainly from the construction of the submarine cables, which is related to the materials of the cables. We assume that the submarine cables in our base case have cable weights of 35 kg/m Copper[17]. The GHG footprint of cable conductor is obtained from the Ecoinvent 3.6 database, which is 7.99 kg CO2e/kg Copper. The GHG emissions of submarine cable is shown by equation (5).

$$GHG_{cable} = N * G * L * GHG_{Copper} \quad (5)$$

Where is the GHG emission of subsea transmission (kg CO2e), is the number of submarine cables, is the submarine cable weight (kg Copper/m), is the submarine cable length (m), and is the conductor GHG footprint (kg CO2e/kg Copper).

The GHG footprint of the HVDC chain shows the CO_2e emission per delivered power, which can be obtained by equation (6).

$$GHG_{HVDC\ chain} = \frac{GHG_{PV}+GHG_{EES}+GHG_{cable}}{P_{AC\ grid}} \quad (6)$$

Where is the GHG footprint of the HVDC chain (kg CO2e/MWh), is the GHG emission of PV plant (kg

CO2e), is the GHG emission of energy storage system (kg CO2e), is the GHG emission of submarine cables (kg CO2e), and is the power input of AC grid (MWh).

2.3 Economic assessment

For the PV plant, its CAPEX can be derived from the CAPEX of the base plant that can be found in the literature, according to equation (7)[1].

$$C_{design} = C_{base}(\frac{S_{design}}{S_{base}})^{SF} \quad (7)$$

Where represents the cost of the designed plant, is the cost of base plant in the literature, and are the capacities of designed plant and base plant respectively. specifics the scaling factor, and we take 1 for the PV plant.

The PMT function in Excel can obtain the annual payments of loans (CAPEX) based on the fixed discounted rate and equal instalments, which is described by equation (8).

$$Function = PMT(rate, nper, pv) \quad (8)$$

Where is the discounted rate (in our study, it is 7%), is the total amount paid on loan (in our study, it is 30 years for all parts except that 10 years for the energy storage system) the and is the total present value of a series of future payments (in our study, it is CAPEX of the whole chain).

An operational expenditure (OPEX) is the sum of variable OPEX and fixed OPEX. Variable OPEX varies with the quantity produced, as opposed to fixed OPEX.

$$OPEX = variable\ OPEX + fixed\ OPEX \quad (9)$$

In our study, variable OPEX is neglected, as there is no significant consumption of chemicals or energy. Fixed OPEX covers annual expenses such as labor cost, maintenance, or insurance. It is generally assumed as a certain percentage of CAPEX.

It is found in the literature that PV plants can last for about 25-30 years[18]. The lifetime of the battery storage part is assumed a replacement every 10 years. For cables, the main longest cables which were decommissioned had this operation done after 30-40 years of function[4]. Here, we assume that the lifespan of the HVDC chain is 30 years (except for 10 years of energy storage system).

3 Results

3.1 Energy efficiency

Power input and output of each block can be obtained, and then the energy efficiency of the HVDC chain can be calculated in Table 4.

Table 4. Calculation results of energy efficiency.

Key assumptions	Value	Unit
Installed capacity of PV plant	3.7	GW
Power output of plant	1	GW
Power output of converter station (Australia)	0.99	GW
Power output of subsea transmission	0.75	GW
Power output of converter station (Japan)	0.74	GW
Power input of AC grid	0.74	GW
Energy efficiency of HVDC chain	74	%

Therefore, the energy efficiency of the HVDC chain is 74%, delivering 5920 GWh/y to Japan. The key contributor to power loss is long-distance subsea transmission, accounting for 93%, shown in Fig. 2.

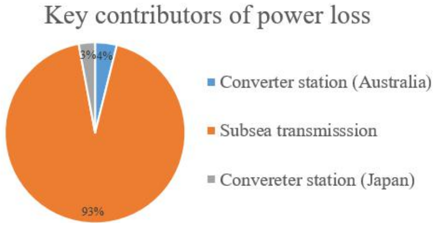


Fig. 2. Key contributors of power loss.

3.2 GHG emission

The GHG emissions of each block of the HVDC chain are listed in Table 5. According to the reference[19], the conversion losses during operation account for 95% of climate impact. In the current study, operation loss of converter represents 1%, which means GHG contribution from converter construction can be neglected in front of submarine cables.

Table 5. GHG emissions of each block of HVDC chain.

GHG emisssions	Value	Unit
PV plant	400	kta CO_2e
Energy storage system	145	kta CO_2e
Submarine cable	181	kta CO_2e

Fig. 3 shows the GHG emissions of the HVDC chain with the copper conductor of submarine cables. The PV plant has the most significant proportion of GHG emissions (around 55%), energy storage system has a share of 20%, and submarine cable shares 25%.

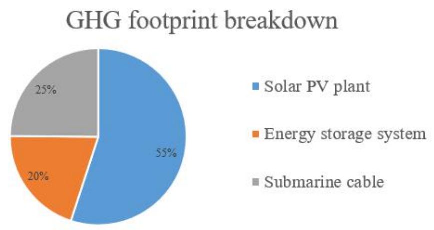


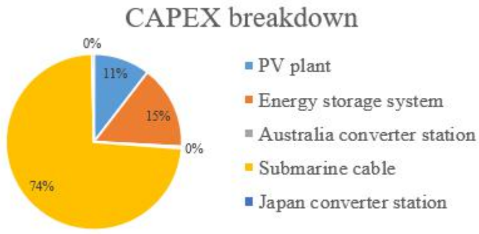
Fig. 3. GHG emissions of HVDC chain.

The GHG footprint of the delivered power is 112 kg CO_2e/MWh chain (compared to 50 kg CO_2e/MWh without battery storage and transport).

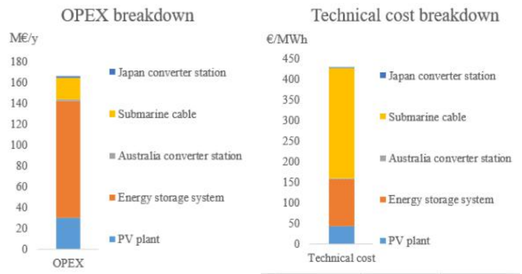
3.3 Cost estimation

To deliver 5920 GWh/y in Japan, CAPEX is 29058 M€, OPEX is 166 M€/y. At the end of the 10th year and 20th year, we need to invest another 4500 M€ for battery replacement.

As illustrated in Fig. 4, The construction and operation of submarine cables are the main components of the technical cost (around 65%). Renewable power plant and energy storage system are also essential parts (around 35%), and the technical cost of converter stations are too small so that it can be ignored.



(a)



(b) (c)

Fig. 4. (a) CAPEX breakdown, (b) OPEX breakdown, (c) Technical cost breakdown.

4 Sensitivity analysis

There are uncertainties in the assumptions used in this analysis. Hence, sensibility analysis is conducted to assess the influence degree of key parameters on the performance of our HVDC value chain. The selected key parameters and the range of their values for sensitivity analysis are listed in Table 6.

Table 6. Base case, better case and worse case for sensitivity analysis.

Key parameters	Better	Base	Worse	Unit
Submarine transport power loss	1.6	2.5	3.5	%/1000 km
PV plant availability	30	27	15	%
Battery storage installed capacity	19	19	38	GWh
GHG footprint of energy storage plant	40	75	110	kg CO_2e/kWh
CAPEX of submarine cables	0.73	1.7	3.1	M€/km
Submarine cable length	9700	9700	12700	km
Power plant lifetime	40	30	20	years
Submarine cable lifetime	40	30	20	years

The results of sensitivity analysis on the technical cost of the HVDC chain are shown in Fig. 5. CAPEX of submarine cables has an enormous impact on the technical cost of the HVDC chain, followed by submarine cable length, power plant availability, energy storage installed capacity of PV plant, and submarine transport power loss. By contrast, the impacts of PV plant lifetime and submarine cable lifetime are limited.

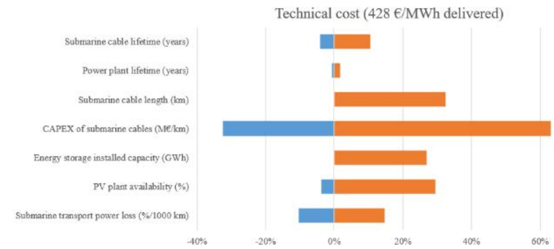


Fig. 5. Sensitivity analysis on technical cost of HVDC chain.

The results of sensitivity analysis on GHG emission of the HVDC chain are shown in Fig. 6. Submarine transport power loss and PV plant availability are the major factors influencing GHG footprint. Other factors, including submarine cable length, the GHG footprint of the energy storage plant, and energy storage installed capacity, have similar impacts on the GHG footprint of the whole chain.

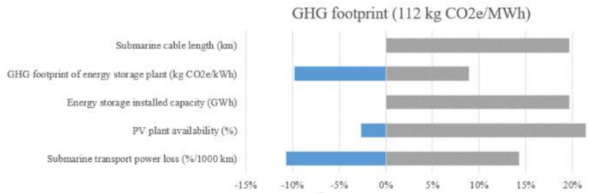


Fig. 6. Sensitivity analysis on GHG footprint.

To sum up, submarine cable length, power loss and lifetime, battery storage system sizing, and power plant availability have a significant impact on the whole chain's cost and GHG performance. These parameters should be carefully investigated if we would like to develop an HVDC chain for power transport.

5 Conclusion

This paper aims to evaluate the long-distance transport of green power through HVDC submarine cables based on technical, economic, and environmental assessments.

8000 GWh/y power is generated by a PV power plant, of which 5920 GWh is delivered in Japan. The energy efficiency of the HVDC chain is 74%, and 93% of power loss is due to long-distance submarine transmission.

Considering 5920 GWh delivered to Japan, the GHG footprint is around 112 kg CO_2e/MWh. PV plant has the most significant proportion of 55%, followed by 25% of submarine cable and 20% of the energy storage system.

The CAPEX is 29058 MW. The materials and installation of submarine cables are primary components of CAPEX, which account for 74%. Annual OPEX is 166 MW/y. Renewable power plants and battery storage systems are the main proportions. The technical costs are 428 €/MWh. Submarine cable cost is the primary source of the HVDC chain in technical cost, around 65% of submarine cable cost followed by 30% of the PV plant and energy storage cost.

Sensitivity analyses show that, for economic performance, CAPEX of submarine cables has a dominant impact, and for environmental performance, power plant availability has the most considerable impact.

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