**Review of global HVDC subsea cable projects and the application of sea electrodes**

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**ABSTRACT**

Sea electrodes have been used since the first HVDC subsea links were installed in the 1950s and provide a simple proven solution for the return current path. Today around 30% of the approximately 40 HVDC subsea links in service use sea electrodes as the return current path under normal or emergency operation conditions. This paper reviews the evolution of interconnectors with sea electrodes and the factors, such as location, environmental impact, current capacity and financial factors (cost, flexibility, losses) which need to be assessed before adopting a sea electrode. In particular findings from environmental studies undertaken on existing sea electrodes are reviewed, as well as, the detailed content of recent Environmental Impact Statements for HVDC projects with proposed sea returns. Finally, the reasons for a change in design on links with a proposed sea return to a metallic return are also considered.

**Keywords:** HVDC, Cable, Subsea Cable, Marine electrode, Sea electrode, Return path

**1. INTRODUCTION**

HVDC has formed part of the electricity transportation mix since Edison’s first network in New York in the 1880s. Since that time the technology has evolved many times, progressively allowing more power to be transmitted over ever longer distances. The first subsea HVDC link was installed between the island of Gotland and the Swedish mainland in 1954 [1]. Since then approximately 50 HVDC subsea connections have been commissioned (Figure 1), resulting in over 40 operating links today; with more in construction and many others in the planning phase [2]: data based on a revision and updating of [3]. In recent years the number of HVDC subsea links in service has grown rapidly driven by factors including:

1. Liberalisation of the electricity market in Europe – electricity trading between countries across the continent has created an environment where the construction of inter-country HVDC subsea links has become economical. These new interconnections drive down electricity costs for consumers and also increase security of supply. In the longer term a more highly interconnected Europe allows renewable electricity to be moved from areas of high generation to regions of high demand more efficiently, or transported to regions with energy storage capacity such as pumped hydro facilities in Norway.
2. New technology – new convertor station technology, such as voltage-source convertors (VSC) with their advantages over previous technology have created new opportunities for HVDC connections. Additionally the rapid advancement in maximum operating voltage of VSC convertor stations has further improved the economic case for HVDC links.
3. Security of supply – subsea HVDC cables have also been installed to connect to the mainland to nearby islands [1,4] or interconnect groups of islands [5-7]. Such links help meets customers’ expectations for more reliable electricity. Additionally, these connections often allow old inefficient/costly generating equipment on the island(s) to be run less frequently or even retired, with the additional benefit of reduced CO2 emissions.

Every HVDC subsea connection is unique and designed taking into account the many project specific requirements [8] including:

* Length – distance between the convertor stations, as well as the length of subsea cable. Convertor stations may be situated some distance from the cable landing points: the on-shore connection may either be made by continuing the cable or migration to overhead line.
* Power transfer – is usually determined by the utilities at either end of the link and the local capabilities of the power grids.
* Losses – these need to consider the contribution from both the convertor stations, land and subsea cables, any overhead lines, and the electrode system if included in the design. The lifetime cost of losses is often factored into the commercial assessment of competing project designs.
* One or two-way power flow – usually dictated by the intended use, hence a load centre connected to a region of generation will typically have a one-way flow, whereas an interconnection intended to energy trading will most likely be two-way.
* Reliability – some projects are designed to still operate following an outage on an HVDC cable, either at reduced load or through the switching in of a spare cable.
* Black start capability – particularly important for connections to offshore platforms, windfarms or islands.

All these choices affect both the convertor station design and subsea component selection. Crucially for an HVDC system the power must flow from the “sending” convertor station to the “receiving” convertor station and back again. It is the path by which the electricity returns which is the focus of this review and in particular the evidence supporting the use of sea electrode systems.

**2. RETURN PATH OPTIONS**

There are four main options available for the current return path [8-10].

**Bipole** –This typically consists of two identical HVDC subsea cables connecting the sending and receiving convertor stations; one cable operates at positive polarity and the other negative polarity. The return current flows through the cable(s) between the receiving and sending convertor station.

**Metallic return** – The HVDC cable system usually consists of a single HVDC (monopolar) cable and a medium voltage (~20 kV) cable connecting the receiving and sending convertor stations to carry the return current. The medium voltage (MV) cable is either bundled with the HVDC cable or laid in a separate trench. Recently cable constructions integrating the MV metallic return with the HVDC cable have become available: this simplifies cable laying but complicates cable manufacture and repairs.

**Ground electrodes** – Like the metallic return configuration but without any continuous metallic return path for the current between the receiving and sending convertor station; instead the current passes through the earth between arrays of electrodes (typically buried at a depth of 50-100 m) at either end of the link. Such a design is uncommon for HVDC subsea links since the sea provides a better electrical path for the current.

**Sea electrodes** – These rely on the inherent electrical conductivity of the seawater to carry the return current and as with ground electrode systems have no continuous metallic path: in reality a large proportion of the current flows deeply through the earth. There are three typical sea electrode configurations:

1. Shore – An array of electrodes is buried on land, often on the beach or a few metres back from the beach, and at a depth to ensure contact with salt water.
2. Pond – An electrode array is installed in a man-made harbour or lagoon. The individual sub-electrodes are either attached to the harbour wall or hung from a pontoon within the lagoon (Figure 2).
3. Marine – Either a long bare conductor (often in a ring configuration) or an electrode array installed on the seabed typically a few kilometres offshore in water less than 20 m deep (Figure 2).

**3. RETURN PATH SELECTION FACTORS**

Sea electrode systems have been installed since the 1950s and are still being designed and installed today [1, 11-14]. The decision to choose a sea electrode system is a balance of many factors and their relative importance will be specific to the project; some of these key factors are briefly described below in alphabetical order.

**3.1 Environmental considerations**

The impact of electrolysis products generated at the cathode and anode of sea electrodes, most notably chlorine and bromine at the anode and associated by-products, on marine organisms has been a point of opposition to the use of sea electrodes. Sea electrodes also generate an electric field which can be sensed by some sea creatures and potentially felt by humans in the water or walking across the beach above buried shore electrodes if the local field strength is too high. Additionally the current flowing in HVDC cables, metallic return cables, or to a much lesser extent through the sea in the case of sea electrodes, generates a static magnetic field which can be sensed by some marine creatures; the influence of this field on behaviour, particularly migration, has been raised in opposition to HVDC projects. All of these environmental concerns will be reviewed in more detail below.

**3.2 Financial considerations**

Options for the return current path for monopolar HVDC cable systems are either a metallic return cable or sea/ground electrodes. As the length of a subsea link increases the cost of the corresponding metallic return increases proportionately due to the investment in cable and installation. In contrast, for a particular design/current capacity, sea electrode systems have a fixed cost irrespective of the length of the link; this includes the cost of electrode array materials and construction/installation at or near the shore. Consequently, sea electrodes systems are economically more attractive for longer HVDC subsea links.

Life cycle cost considerations also favour sea electrode systems over metallic returns due to the lower electrical resistance of the return path through the sea (and sub-seabed layers) than a metallic return and consequent lower electrical losses [15].

**3.3 Increased flexibility**

HVDC cable systems designed as bipoles or monopoles with a metallic return may still be designed with a sea electrode system for use in emergency operation. In the event of an HVDC cable fault on a bipole, the link can be operated at half power using the sea electrode system to carry the return current. A fault on the metallic return of a monopole can similarly be accommodated using the sea return and power flow maintained. The bipole plus sea electrode design can arise when an existing monopole with sea electrodes is upgraded to a bipole by adding another HVDC cable, such as in the case of the Skagerrak and Fenno-Skan links [16,17].

**3.4 Location**

Even if a sea electrode system is the preferred technical solution it still requires a suitable installation site. Shore electrodes need a suitable beach in which to bury the electrode array (ie not on bedrock). Pond electrodes require either a bay or suitable shoreline along which a harbour wall or permeable berm may be built; both also require access during construction and afterwards for maintenance activities. Marine electrodes require an area of seabed into which a bare copper conductor ring cathode can be buried (this is typically one kilometre in diameter), for example Fenno-Skan 1 or Kontek [17,18], or as in the case of the Konti-Skan and Fenno-Skan an area of seafloor on which the electrode array elements can be laid out [18,19].

**3.5 Operation and maintenance**

Sea or ground electrode systems may need periodic maintenance such as removal of deposits building up on the electrode elements or replacement of the elements due to electrochemical erosion [16,17]. Metallic return cables are essentially maintenance free but present the risk of damage from ships anchors or fishing gear; this can lead to long repair times and financial losses if the link is used for energy trading. Similarly, marine electrodes installed on the sea floor can be damaged by anchors or fishing activity; the use of multiple electrode elements helps spread this risk although damage to the main cable connection back to shore risks taking the entire sea electrode out of service.

**3.6 Stray currents**

There are many metallic structures in the sea other than HVDC cables, such as, pipelines, other cabling, ship wrecks and oil platforms. All can be subject to electrolytic corrosion caused by the induced current from the sea electrode system exiting the object [22]. The induced current is related to the local field strength (which decreases with distance from the electrodes), object size and alignment with the field. Predictions of electrolytic corrosion are usually based on seabed surveys to identify objects at risk and finite element models, large objects like pipelines up to 50 km from the electrodes are typically considered within these calculations [23]. HVDC systems with metallic returns do not cause these issues since there is no electric field in the sea.

**4. ELECTRODE MATERIAL OPTIONS**

Depending on the type of sea electrode installation many materials can and have been used to form the electrode elements. Since the first installations in the 1950s materials selection has evolved as better solutions have been identified and experience has been gained from in-service systems. Research continues into innovative alternative electrode solutions [24]. Examples of typical working systems are given in the following section.

**4.1 Cathode**

Hydrogen is generated at the cathode which is considered of lesser environmental concern than chlorine evolved at the anode. Typically cathodes consist of either:

1. Bare copper conductor laid on the seabed or shallowly buried – the conductor is often buried in a ring-configuration such as the 1500 m by 700 m loop of 300 mm2 copper conductor used for the Fenno-Skan 1 cathode [18] which is capable of carrying 1280 A. Alternatively bare copper conductor can be laid in a linear arrangement roughly parallel to the coast; the SAPEI cathode consists of two conductors each 300 m long laid on the sea floor eight kilometres offshore [25]. Bare copper conductor has only been used in a marine environment.
2. Graphite rods surrounded by coke – this option is used for both shoreline and marine electrodes, and has been deployed since the earliest HVDC subsea projects. Skagerrak 1&2 employs a 1000 A capacity graphite/coke cathode and was designed based on experience gained from the earlier Konti-Skan interconnector [26]. The Danish electrode initially comprised of 41 parallel connected graphite electrodes, each held in 0.6 m deep concrete rings 2.5 m in diameter and filled with coke, and spaced 8 m apart along the shoreline [9,18,27]: the number of electrodes was later doubled due to higher than expected ground resistance. The Norwegian end of the link has 61 series connected elements contained in coke-filled wooden structures.

**4.2 Anode**

Chlorine and oxygen are produced at the anode with the ratio of the gases evolved controlled by factors including the anode material, pH, salinity, temperature and current density. Increasing the surface area of the anode elements and ensuring good water exchange increases the selectivity for oxygen reducing chlorine generation. Good water movement also disperses the chlorinated and brominated compounds formed in side-reactions close to the anode surface.

Graphite/coke electrodes can also be used for the anode (as previously described for the cathode) and have been used on projects such as Konti-Skan and Skaggerak [18,27]. Titanium rods or meshes are often used in pond and marine electrode systems respectively. Due to its higher oxygen selectivity compared to graphite/coke, titanium anodes generates less chlorine. Moreover, for pond electrode systems where space is generally limited, large graphite/coke electrode elements may be impractical, whereas suspended titanium tubes, as used on the SACOI project, are a more practical compact solution [9,18,27]. Oxygen selectivity can be further enhanced by coating titanium with mixtures of noble metal oxides. Such electrode elements were deployed on SACOI during a 1995 refurbishment [18]. The 1700 A Fenno-Skan 2 anode in Sweden has forty shallowly buried 20 m2 titanium meshes coated with a special oxide coating of precious metals [19]. The Baltic Cable has a similar number of anode elements laid on the seabed under plastic tubes and stones [28]. The early projects, such as the Inter-Island link in New Zealand, deployed linseed oil impregnated carbon rod anodes but these eroded and were later replaced with silicon-iron [21].

**4.3 Reversible polarity electrodes**

Bidirectional links require both electrodes to operate as either cathode or anode depending on the direction of power flow. Although all the electrodes discussed above can act in this manner, some are subject to electrolytic erosion under reverse polarity conditions. Noble metal oxide coated titanium and graphite/coke are the most commonly deployed bidirectional electrode types. Where existing monopolar HVDC subsea cable links are upgraded to a bipole the original cathode may need replacement. For example, the bare copper conductor cathode of Fenno-Skan 1 was replaced with coated titanium meshes when the link was converted to a bipole with the addition of the Fenno-Skan 2 cable. In contrast, the SAPEI link although designed as a bipole ordinarily operates with power flowing from Sardinia to the Italian peninsula and the electrode system is designed accordingly; coated titanium rod anode and bare copper conductor cathode. To confirm the performance under reverse polarity conditions the link owner undertook a testing programme which showed “no surface alteration” to the titanium rods operated as a cathode and 0.2% loss per year for the bare copper conductor when operated as an anode [29].

**5. OPERATING HVDC SUBSEA LINKS**

Presently 30% of all operating HVDC subsea cable links are installed with sea electrodes (Figure 3). Table 1 provides technical information relating to the 14 subsea links installed with a sea electrode system including modification and upgrades to the links since original commissioning. Each end of the HVDC subsea link needs to be considered separately since it is not uncommon to have different types of electrode at either end, for example, the multi-terminal SACOI link has a marine, a pond and a land electrode [30]. Other examples where sea electrodes are used in combination with land electrodes include the Baltic Cable and New Zealand’s Inter-Island connection [19,21,28]. From Figure 3 it can be seen no particular sea electrode type dominates, marine, shore and pond electrodes are deployed in approximately equal numbers.

This simple analysis nevertheless misses the geographical variation of sea electrode types; marine and shore electrodes dominate in the Baltic Sea, Kattegat and Skagerrak, and pond electrodes are frequently applied in the Mediterranean on links connected to Italy. The transmission companies in these regions have acquired considerable knowledge and expertise operating these particular designs and have replicated these on new projects. Additionally, factors such as the local geography need to be considered; the shallowly sloping seabed of the Baltic Sea favours marine or shore electrodes rather than pond electrode installations.

During the decades since the first subsea HVDC links were installed there has been a progressive rise in the power transfer capability of new projects, through a combination of higher operating voltage and current rating. Likewise as interconnections have needed refurbishment, old convertor stations have been replaced with higher voltage equivalents and in some cases the cables of the oldest links have been replaced with higher voltage cables. Consequently, the current handling capability of the sea electrode systems has had to increase. Figure 4 shows the evolution of sea electrode current capacity since the original Gotland link in 1954 to the present day. The highest current capability electrode, 2500 A, is the Punta Tramontana pond electrode which is shared by both the SACOI 2 and SAPEI links between Sardinia and the Italian peninsula.

There are an additional dozen HVDC subsea projects which are due to commission before the end of the decade showing a further increase compared to the previous five year period (Figure 1). A number of these links, some of which are already under construction, will employ sea electrodes (Table 1), namely, MonIta (Montenegro – Italy), the Maritime Link (Canada) and the Labrador Island Link (Canada): the latter is discussed in more detail below.

**6. ENVIRONMENTAL MONITORING OF OPERATIONAL SEA ELECTRODES**

Studies have been carried out in a number of regions into the environmental impact of installing and operating sea electrode systems. These monitoring studies have principally considered:

1. Disturbance of the environment during installation
2. Impact of the electric field and magnetic field generated during operation
3. Impact of electrolysis products evolved during operation
4. Impact of stray currents during operation both onshore and offshore

Monitoring programmes have been undertaken ever since the first links were installed [31] and initiated for a variety of reasons including voluntary studies of the operational interconnector by the owner, conditions applied during the permitting of the project or data gathering to support upgrades to an HVDC link. For example, the Swedish Water Right Court ruled that fisheries and water pipes in the region near the Baltic Cable should be monitored for five years after commissioning; this was later extended for a further two years.

**6.1 Flora and fauna**

Considerable environmental monitoring has been undertaken of the HVDC links in the Baltic Sea, Skagerrak and Kattegat. The influence of the magnetic field generated by the Baltic Cable on migrating eels was of particular public concern during project development. However, in 1999 the Swedish National Board of Fisheries concluded, “nothing has emerged to indicate that the cable prevents the large-scale migration of silver eel out of the Baltic Sea” [32] and the Fisheries Agency noted, “that the magnetic fields around the Baltic Cable admittedly makes eels muddled, but the cable is no obstacle to eel migration out of the Baltic Sea”. Other projects in the region raised similar concerns such that during the development phase for the Viking Cable project research was carried out on the effect of magnetic fields on baby eels [Hock cited in 33]. Similarly for the Kontek project Debus reviewed the influence of electric and magnetic fields on aquatic organisms (particularly migratory species) [34].

Many studies have examined flora and fauna at sea electrodes sites and control locations both before and after installation. Observations of this type on benthic species along the Baltic Cable route showed that given the, “significant differences in biomass, abundance and number of species, it is not possible to discern any trend …… any impact on the benthos beyond the natural variation does not seem to exist” [35]. Likewise at the sea electrode and control sites, “no difference in the re-colonization was observed when comparing the test areas of the electrode station and the reference”. Dredging and bottom grab samples collected in successive years inside and outside the Kontek ring cathode revealed large variations in epifauna and infauna population densities although no statistically relevant trends were evident [36]. Similar before and after laying studies of the Swepol cable concluded, “one year after construction there were no obvious changes in macrozoobenthos species composition, abundance or biomass” [Andrulewicz 2001 cited in 23,37]. Video observations of the Konti-Skan graphite/coke electrodes showed crabs and starfish living directly on the electrodes [Nielson cited in 33] and fish were observed near the electrodes in an estimated 6 V/m field [33].

Away from the Baltic Sea region anecdotal evidence in the Basslink Draft Integrated Impact Assessment Statement (DIIAS) [22] claims no impact from the SACOI project on the 28 shark species found around the Italian peninsula, or change in shark or ray numbers in the waters around the Leyte – Luzon electrodes where the electric field is highest.

Surveys prior to the upgrading of the New Zealand Inter-Island link near the shore electrode and further along the coast found no differences in algae, edible shellfish or fish species. Additionally, there had been no reports of fish, sharks or marine mammals being attracted to the Te Hikowhenua shore electrode site [21]. Electric field measurements and observations near the electrode and in the Cook Strait concluded that the HVDC cable system did not disturb the general ecology or behaviour of sharks and rays in the surrounding waters [38].

Measurements at the Baltic Cable anode and a reference site revealed no differences in seawater pH between the locations and measurements of hypochlorite at the anode showed concentrations 100 times lower than that used in the chlorination of drinking water [23]. Organic chlorine uptake by caged mussels and clams showed only one occurrence of elevated levels at a reference site and none at the sea electrode site compared to the natural background: all measurements were “very low compared with levels that cause toxic effects in organisms” [33]. Likewise no accumulation of halogenated compounds was found in mussels or sediments near the Kontek anode [33]. Sediment samples taken close to the Skagerrak graphite/coke anode and a remote reference site also revealed no negative environmental accumulation of chlorine and halogenated compounds [33].

On land, spiders and other insects have been reported to live successfully inside the buried shoreline electrode cells chambers of the New Zealand Inter-Island link seemingly unaffected by the electrolysis products evolved [21]. Chlorine given off by the Vancouver Island link shoreline electrode at Boundary Bay has been reported to destroy vegetation for up to 0.2 m around each electrode element [39].

In conclusion none of the published studies has reported any significant negative impacts from the operation of sea electrode systems. A similar view has also been reached by the Baltic Marine Environment Protection Commission (Helcom) in its Initial Holistic Assessment which monitors and reports on the impact of man’s activities in the region. The report ranked noise and smothering (from sediment disturbance) caused during cable laying as, 54 and 55 respectively, out of 62 assessed potential pressures in the Baltic Sea [40]: any impacts caused during the operation of the interconnectors fail to register on the list.

**6.2 Stray currents**

The electrical current flowing between the cathode and anode will take the path of least resistance which on occasion can cause stray current to flow in metal structures such as pipelines in the sea or power grids onshore. The magnitude of the current depends on the size and orientation of the metal object and the local electric field, which is related to distance from the sea electrode. If the magnitude of the current exiting the object is greater than a particular threshold then corrosion can occur. Most of the reported problems have been on the oldest links, however, since that time the ability to predict corrosion issues has greatly improved.

Cable armour corrosion was identified during a condition assessment of the Vancouver Island HVDC cable after 30 years of service; in 2005 corrosion protection was installed in the Trincomali Channel to mitigate the issue. When planning the SAPEI link, field measurements from the existing SACOI 2 anode were used to predict possible corrosion issues from the new sea return. These results predicted a current density less than 5 mA/m2 five kilometres from the anode; such a current density had previously been shown to cause very low levels of erosion over a 20 year period for iron and lead. The closest cables to the anode are 8 km from the electrode and hence safe from corrosion. At the end of the Baltic Cable probationary period in 2002 the Swedish Environmental Court concluded that the electrode system had caused no corrosive effect on the water pipes in Smygehamn during the seven year monitoring period.

Following commissioning the New Zealand Inter-Island link initially operated as a monopole. Some very minor electrolytic corrosion of water piping and neutral earthing conductors was discovered at a farm near the Bog Roy electrode (acting at the time as the cathode) [21]. Some years later corrosion issues were experienced with newly erected fence wire near the other electrode site; posts and battens treated with metallic salt preservatives caused fence wires to corrode at the staple positions [21]. Inserting small insulators into the wires limited the current solving the problem [9]. Similarly the Vancouver Island link also initially caused some stray current corrosion issues including failure of TV antenna tower anchor rods and, damage to water pipes and sewer mains [9].

Following upgrading the New Zealand Inter-Island link in 1992, which doubled the current carrying capacity of the sea return, a number of issues were experienced on the local AC power network caused by the return current [21]. Earth return current entering the convertor transformer through the earthed star point caused DC magnetic saturation and in turn second order harmonics. The same problem caused a power station 10 km from Benmore convertor station to trip on differential protection. Measurements and analysis led to neutral earthing resistors being installed to transformers at a number of sites on the North and South Islands: special earthing resistor arrangements were required at two sites. Finally overhead lines maintenance procedures for the north-south lines from Benmore (which act as a parallel earth return path) have required modification to account of the risk of DC current arcs forming when temporary earths are removed; this risk only arises when the interconnector is operating as a monopole under high load conditions.

In summary, stray currents have been seen to cause interference on AC power networks and corrosion. Nevertheless, these problems have been generally only reported on the oldest links. Modern modelling methods enable the distribution of stray currents through the sea and rock layers to be better predicted and their impact assessed during the design phase of a project allowing appropriate mitigation to be taken long before any problems arise.

**7. DETAILED EXAMINATION OF ENVIRONMENTAL IMPACT STATEMENTS**

Although environmental protection has always been considered during the planning of HVDC subsea connections, changing public awareness of environmental issues has resulted in better documented environmental assessments for more recent projects. Projects, particularly those installed during the 1990s in the Baltic Sea region, have provided valuable information on the actual impacts of different sea electrodes types through detailed post-installation environmental studies.

Today, every new project produces some form of Environmental Impact Statement (EIS) compliant with local legal requirements which is unique to the project, and more specifically, to the plants and animals in the vicinity. For the marine environment most EISs consider the following categories:

1. Algae
2. Plankton – phytoplankton, zooplankton, eggs and larvae of macro invertebrates, and ichthyoplankton
3. Benthic invertebrates
4. Demersal fish
5. Pelagic fish including migratory species
6. Invertebrates – both those of commercial value (shellfish) and non-commercial
7. Turtles
8. Mammals – Whales and seals
9. Seabirds

The following section reviews the evidence in the EIS and supporting documentation for Basslink and Labrador Island Link (LIL); these represent different proposed sea electrode solutions, namely, pond electrodes in the case of LIL and marine electrodes for Basslink. Although the LIL project electrodes are under construction, Basslink ultimately choose to install a metallic return. Written a decade after the Basslink DIIAS, the LIL EIS cites much of the same scientific literature however also contains new studies, and as expected, a number of investigations specific to the Strait of Belle Isle and Conception Bay [41]. The LIL EIS assumes that no invertebrates or fish will enter the ponds containing the electrode elements.

**7.1 Installation**

The LIL EIS assesses the impact of constructing pond electrodes at L’Anse au Diable and Dowden’s Point [41,42], as well as horizontal drilling for the cable landings and cable laying activities. Adverse effects were identified for fish during berm construction due to loss of habitat, and more generally, “sub‐lethal/lethal physical effects on benthic biota” caused by rock dumping activities. The increased turbidity from seabed disturbance is predicted to return to normal levels in 1 to 100 hours. Overall these factors were assessed to be localised, of short duration, and of low to moderate impact. Similarly, installation of the Basslink marine electrodes (graphite/coke anode and bare copper conductor ring cathode) by a combination of wet-jetting and trench cutting would also have led to a temporary reduction in water clarity. This was expected to return to background levels within an hour even for the finer sediments [22]; consequently, the impact on phytoplankton, benthic algae or macroinvertebrates was assessed not to be significant.

Localised noise caused during the Basslink electrode installation was predicted to drive fish temporarily from the immediate area only for them to return following cessation of the work. Underwater noise from constructing the LIL rock berms and cable laying activities was predicted to have the greatest potential to affect marine mammals and turtles. The LIL EIS reviews the scientific literature on the hearing range of marine mammals and turtles, and their observed behaviours in response to boat/construction noise [42]; sound pressure calculations were accordingly undertaken. This EIS predicts that the potential for permanent or temporary hearing loss for whales, seals or turtles is negligible, and that minimal behavioural effects are expected with at worst the animals avoiding the noise source. Similarly whales and dolphins in the Bass Strait were expected to avoid the cable laying vessels [22].

The LIL EIS also reviews the probable responses of shore and nesting birds to construction noise based on the auditory ability of different species present in the area [42]. It predicts birds feeding or roosting near the work sites will likely relocate if disturbed to adjacent coves where similar habitat exists, resulting in minimal overall impact. Moreover, to reduce the impact on nesting birds mitigation measures were recommended, such as using well-maintained engine mufflers.

**7.2 Operation**

Table 2 summarises the predicted environmental impact of the electric field, magnetic field and electrolysis products generated by the proposed electrode systems detailed in the Basslink and LIL EISs on a range of biota. Not all biota categories are assessed in all cases due to the design of the electrode systems, for example, birds will not come close enough to the Basslink marine electrodes to sense either the electric or magnetic field and therefore are not considered in the EIS. The following section briefly reviews the considerable evidence detailed in both EISs.

**7.2.1 Electric field**

The initial DIIAS for the Basslink project contains a thorough review of the known effects of electric fields on marine organisms [22]. At maximum power transfer, 1500 A, the electric field at the anode surface was calculated to be 1.000 V/m dropping to 0.048 V/m one metre away; the corresponding values at the cathode were 1.995 V/m and 0.019 V/m. These fields are approximately the same or lower than for sea electrodes operating in the Baltic Sea, consequently based on previous evidence the impact of these fields on most flora and fauna was predicted to be not significant. However, the DIIAS conceded that, due to the ability of sharks to detect fields as low as 0.5 μV/m, a large shark within a few metres of the electrodes may detect a potential difference between its head and tail which may influence behaviour; either repelling or attracting the shark. The LIL EIS similarly concludes that sharks/rays (elasmobranches) and bony fish (teleosts) outside the berms may detect the electric field from the electrodes but behavioural change is unlikely. The maximum electric field predicted at the surface of any Basslink subanode, or at the seabed above the cathode, is below 0.2 V/m. The DIIAS claims this is “well below the 1.25 V/m limit for sea electrodes accessible to marine mammals” and consequently that no impact on marine mammals was expected.

The same maximum 1.25 V/m design criterion [43] for the electric field immediately outside the berm was used for the LIL project. In the ponds the maximum field at the electrode elements under full monopolar load was calculated to be 16.7 V/m [44] and the LIL EIS states that “phytoplankton and zooplankton occurring close to the cables and electrodes could potentially be affected. However, any effect is expected to be minimal and the zone of influence is likely to be small” [42]: phytoplankton and zooplankton are important since they represent the bottom of the food chain.

For seabirds that land on the saltwater electrode ponds the LIL EIS argues that “the electric field strength is not likely to cause more than an unpleasant sensation rather than injury or mortality, the response to which would likely be a minor change in behaviour, i.e., the birds would leave”. The operational impact of electrode system was consequently judged minimal [42].

**7.2.2 Magnetic field**

Although the HVDC cable(s) generate the predominant magnetic field associated with any link, the electrical current flowing between the sea electrodes also generates a weak magnetic field. Based on the available scientific evidence the LIL EIS conservatively adopted 200 nT as the minimum field which of could be detected by some marine fauna. Modelling predicts this field to be exceeded within 50 to 100 m from the pond electrodes under normal bipolar operation and 500 m under emergency monopolar operation [42]. The earth’s magnet field is around 50 µT and according to the National Oceanic and Atmospheric Administration (NOAA) there are more than 27 geomagnetic events per year which exceed 200 nT caused by spatial (strength, inclination, local magnetic anomalies) and temporal (daily disturbances caused by solar activity) variations in the earth’s magnetic field.

In the case of Basslink, although no specific field threshold was considered, the influence on migratory magneto-sensitive species was a key consideration. Since the migration routes are far from the inshore electrode sites both projects conclude the weak localised field will have no significant impact on migration or behaviour. The magnetic field from the HVDC cables was considered separately by both projects but the same conclusion reached [22,42].

The magneto-sensitivity of many whales, porpoises and turtles is not well understood and it is believed that some elasmobranches are able to use their electro-sensitivity to detect the earth’s magnetic field. Both projects review the scientific evidence and observations such as harbour porpoises migrating over HVDC links in the Baltic Sea and cetaceans routinely pass through the Cook Strait (New Zealand) without incident. The Basslink DIIAS also reviews the evidence for whale strandings being caused by variations in the earth’s magnetic field or the fields generated by the HVDC cable links and concludes no causal link between natural magnetic anomalies and strandings has been found.

The magnetic field generated by the current in the HVDC cable(s), cable connection to marine electrode arrays and sea can all cause a deviation to ships’ magnetic compasses. The Basslink DIIAS proposed mitigation including updating maritime charts with the installed cable route and warnings to mariners. LIL’s pond electrodes are predicted to cause magnetic compass deviation in excess of 0.5° up to 500 m from both electrodes under emergency maximum load monopolar operation [13] and only exceed 0.1° within 100 m from the berms under normal bipolar operation.

**7.2.3 Electrolysis products**

The Basslink DIIAS provides a thorough summary of the electrolysis chemistry of seawater and the subsequent chemical compounds that can be generated by side reactions. The key issues related to these products are:

* Impact on water quality near the sea electrodes
* Toxicity of the chemicals generated - chlorine, chlorine-produced oxidants and halogenated organic compounds
* Bioaccumulation of these compounds in the food chain
* Implications for marine resources such as commercial or leisure fishing

Both Basslink and LIL chose conservative approaches when estimating the quantities of gases and by-products generated. For example, the LIL EIS assumes the worst case for chlorine selectivity based on the planned electrode materials (30%), and that no gas is lost to atmosphere or through the berm wall into the sea; tidal flushing through the porous berm is expected to reduce the predicted values by ~50%. Table 3 summarises the predicted chlorine production per day taking into account local conditions (salinity, temperature, pH, water exchange and electrode design) for both projects [13,22].

Both projects use the same limit, 10 µg/l, for chlorine-produced oxidants and halogenated organic compounds, that can have a negative (toxic) impact on the most sensitive species of marine flora and fauna (invertebrates and fish) based on published toxicity studies [42]. The LIL EIS also includes a lower limit, 1 μg/l, for which fish may display avoidance behaviour [42]. Applying the conservative calculation assumptions, the toxic limit was predicted to be reached within 2 m of each Basslink subanode under full load conditions [22]. Contrastingly under full load bipolar operation the chlorine-compound concentration for the LIL electrode system is more than two orders of magnitude lower than the toxicity limit [13].

Table 2 summarises the predicted impacts of these electrolysis products on the local flora and fauna. The eggs, larvae and the juvenile stages of marine invertebrates are the most sensitive stages in the life cycle; no significant adverse effects were predicted except for “some species or life stages within about 2 m of the subanodes” [22] or close to the electrodes inside the LIL ponds where phytoplankton and zooplankton “could potentially be affected but the zone of influence is likely to be small” [42]. Overall no significant effects are expected with many species likely to populate on and around the electrodes.

Accumulation of organo-halogenated compounds in the surficial sediments inside and outside the berms is considered less than “optimal” due to the nature of the substrate material and its carbon content [42]. Similarly the Basslink discounts the potential for bioaccumulation of chlorine-produced oxidants and halogenated organic compounds in fish, and hence the higher food chain, due to their limited exposure to these electrolysis products [22].

Magnesium hydroxide and calcium hydroxide can accumulate on the cathode [21], thereby reducing its efficiency, if the local current density exceeds ~10 mA/m2 and there is poor water exchange. Consequently the Basslink cathode was designed to have a maximum current density of 8 mA/m2.

**7.2.4 Stray current issues**

Basslink’s proposed offshore marine electrodes would not have caused interference or corrosion with onshore infrastructure but an assessment of marine infrastructure and maritime cultural heritage was carried out. Any wrecks close to the electrodes were wooden and on-board metallic objects too small to suffer corrosion caused by the stray current. Similarly unexploded ordnance on the seabed would be too small to be effected. An outfall pipe was identified near the Victoria electrode site but mitigation through insulated joints or sacrificial electrodes was proposed.

Stray DC currents in the local transmission and distribution systems near the LIL electrode sites are predicted to be below the interference threshold and therefore not of concern. Likewise telephone lines and facilities in the area were predicted to be unaffected due to insulated nature of the telephone circuits. Corrosion to overhead tower foundations or guy-lines near Dowden’s Point is expected to be below levels which would be detrimental to their integrity. However, the stray current at L’Anse au Diable is marginally higher than the limit to cause electrolytic corrosion to a few distribution pole earth rods: mitigation by inspection and replacement can be implemented. Ground potential raise calculations showed that the voltage difference across nearby structures, such as a service marina, bridges and fuel stores would be negligible. In case these were connected to a remote earth (through the power network), no chance of significant corrosion is predicted [44].

**7.2.5 Heat dissipation**

Although temperature rise of seabed sediments is predominantly an issue concerning heat generated by the HVDC cable(s), both Basslink and LIL address the impact of the proposed electrode systems. Modelling of the LIL electrodes predicted a maximum temperature rise of less than 0.5 °C in the seawater ponds under continuous maximum monopolar load [13]. The EIS concludes that any “temperature increase as a result of heat dissipation from the submarine cables and electrodes will be negligible” [42].

The Basslink project needed to consider not only the heat generated by electrode elements but also the cable connection to the sea electrodes. Calculations predicted a seabed temperature rise of a few degrees Celsius immediately above the electrode cables which the DIIAS proposes would increase the metabolism, growth and productivity of local invertebrates. Similar calculations for the sea electrodes predict seawater temperature rise of only 0.5 °C close to the electrode surface.

**8. CHANGES OF DESIGN AWAY FROM SEA ELECTRODES**

Three projects in recent times, namely, Basslink, NorNed and SwePol, were originally conceived with sea electrodes but were ultimately delivered as bipoles or with metallic returns. The reason for these changes is briefly reviewed below along with some of the implications.

The principle environmental issue raised during the SwePol planning phase was chlorine production [37], with the influence of the magnetic field on migrating fish species of secondary concern: the latter being a commonly raised issue in the region in the past. A thorough survey identified metal objects up to 50 km from the electrode sites which could be effected by the sea return current; near the Swedish coast these including sewage pipes, district heating, medium voltage cables and copper protective shielding. However, worries over corrosion do not appear to have been a major issue. Nevertheless, the combined local concerns persuaded the owner to add a metallic return path [45], thereby avoiding delays to the project.

During NorNed’s development a sea return was the preferred technical solution due to the very long connection length, 580 km, and consequent cost of a second cable [33]. To further lower the environmental impact of adopting a sea return NorNed carried out studies on new electrode materials that would selectively produce less chlorine than previous anodes [33]. Nevertheless, during the engineering phase, potential pipeline corrosion issues were identified off The Netherlands coast by detailed finite element modelling. Although, mitigation measures such as sacrificial electrodes have proven highly successful in the past, in this case there were many pipelines to consider. Another possible solution was relocating the sea electrode 60 km offshore, however, this would have necessitated a new electrode design, increased the risk of damage to the electrode cable, increased operational costs and added considerable project risk [33]. Consequently an alternative engineering solution was found, namely, the use of a simplified bipole with no electrodes; the cable consisted of two fully insulated cables bound together in a flat formation in a common armour.

Throughout the Basslink consultation phase and subsequent public inquiry some objections were raised regarding the submarine cable design; the strongest objections however focussed on the deployment of sea electrodes. The Joint Advisory Panel (JAP) was satisfied that the electric and magnetic fields from the sea return would have no significant effect on marine flora and fauna. Nevertheless, there was concern about the toxicity of halogenated by-products generated at the anode, and the JAP was minded to require Basslink to replace the proposed graphite/coke anode with titanium mesh electrodes as a mitigation measure. There was also concern regarding stray DC currents causing possible corrosion to long metallic structures in the vicinity of the electrodes. During the course of Basslink’s development the perception of corrosion issues changed following the construction of a gas pipeline across the Bass Strait. Although the JAP accepted Basslink’s evidence that any corrosion issues could be mitigated (based on testimony from experts who had worked on similar projects in the Baltic Sea), it concluded that “the owners of long metallic structures in and adjacent to the Bass Strait must agree mitigation measures” [46]: unfortunately such agreement could not be found and replacing the electrode system with a metallic return was the only viable alternative.

This design change required a re-examination of the impacts documented in the original environmental assessment [46]. Electric fields and electrolysis products were eliminated, magnetic fields were greatly reduced (dropping to the local earth’s magnetic field within approximately 10 m from the HVDC cable) and there were no significant change in construction impacts or on fisheries. However, heat generation from the bundled cable doubled increasing the temperature gradient in the seabed sediments; revised calculations predicted a worst case seabed temperature rise of less than 1 °C which was judged not significant compared to the original environmental assessment.

The design change had both positive and negative cost implications [46]:

1. Reappraising the metallic return design led to a more cost effective solution than originally proposed. These changes reduced the number of cable laying campaigns from five to three significantly lowering cable laying and shipping costs from Europe.
2. Bundling the HVDC cable with the metallic return cable required only one trench not two as had been originally estimated.
3. The cost of the metallic return cable was partially offset against the cost and installation of the sea electrodes, and the unforeseen costs of corrosion mitigation measures.
4. Joule losses increased by using a metallic return reducing the financial viability of link; these increase by ~10 MW at full load and 3 MW when the power transfer is 300 MW.

Every HVDC subsea link is unique and the route is constrained by many factors including suitable landing points, the onshore transmission network and suitable sites for the convertor stations. Offshore the HVDC cable route needs to consider other infrastructure and sensitive habitats. Consequently, the preferred route is always a compromise of these factors, as well as project cost. In two of the three cases above corrosion issues necessitated the design change away from sea electrodes, and in the other case corrosion was one of the factors considered. Although mitigation factors, such as, sacrificial electrodes have proven successful either the number of structures that need protecting or the unwillingness of third party asset owners to accept such a solution has driven the design change.

**9. DISCUSSION**

The decision to choose sea electrodes for the return path of an HVDC subsea link is a complex one and as discussed above is an interplay of many factors; technical, practical, commercial and environmental. Although every project is unique and needs to be assessed on its own merits, there are however some trends that emerge from projects that have been built with sea electrodes.

Figure 4 shows that the maximum sea return current has effectively peaked at 1500 A since approximately 1990 with just three exceptions; moreover the projects which are presently under construction will have ratings below this value. Nevertheless over this time period the power transfer capacities of the constructed links have risen due to higher operating voltages.

The Punta Tramontana pond anode is shared between the SACOI 2 and SAPEI links and is capable of carrying 2500 A; there are separate cathodes for each kink off the Italian peninsula coast. Although not normally operated at the maximum current, the electrode did see full load during the installation phase of the SAPEI link; once one of the bipole cables was installed the link was operated as a 1000 A monopole during the cable laying and commissioning phase of the other cable: meanwhile SACOI 2 has a current capacity of 1500 A [29,47]. Other interconnections share common sea electrodes, such as the two bipoles of Skagerrak 1 & 2 and Skagerrak 3 & 4, however in this case the loss of a single cable only results in the sea return carrying the current from one bipole [16].

The second exception is the New Zealand Inter-Island link which has seen multiple upgrades to the convertors, cables and both shore and land electrodes since it first went into service in 1965. The original link was designed as ±250 kV 1200 A, but has now been upgraded to ±350 kV and 2000 A continuous (2400 A for a few hours under emergency conditions) [15]. Today such a power transfer capacity (1200 MW) would likely be met with a higher voltage lower current system design, such as the MonIta link, which is also 1200 MW but designed as ±500 kV 1200 A. Lastly, the addition of Fenno-Skan 2 to the existing Fenno-Skan 1 monopole required a redesign of the sea electrodes to be bidirectional and an increase in maximum operating current to 1700 A. Nevertheless, operating as a bipole means the sea current has been reduced to almost zero, only now carry any imbalance currents between the poles. The maximum current will only be required in the event of an outage on one of the HVDC cables.

HVDC cables carrying lower currents reduce Joule losses which is particularly important for connections on which energy is traded. Cables capable of carrying higher currents by necessity have larger conductors (which increases the capital cost) weight and stiffness. It appears that 1500 A is about the optimum serviceable current capacity. The SAPEI and SACOI 2 cables have lower currents, it is only the shared electrode with a higher (2500 A) capacity and, in New Zealand the Inter-Island link HVDC cables are only 40 km long hence losses will be comparatively low. The use of sea electrodes reduces the total losses since they offer a lower resistance path for the current than either an HVDC cable or MV metallic return cable [15].

The assumption that longer HVDC subsea links favour the use of sea electrodes does not on first inspection of the data appear correct (Figure 5), with only one of the four longest operational links employing sea electrodes. However, as previously discussed both NorNed and Basslink were designed with sea returns until potential corrosion issues caused a design change. The 292 km connection to the Norwegian Valhall oil and gas field requires VSC technology (to support black start capability) and uses an integrated return conductor negating the need for either a separate return cable or an electrode system.

All the published studies which have monitored the installation and operation of HVDC subsea links with sea electrodes have revealed no significant impact on flora and fauna. These field studies and additional scientific research have been used as the basis for the environmental impact assessments and environmental impact statements for subsequent proposed projects. These long comprehensive detailed documents rely heavily on the limited number of field studies, supplemented with specific local information on flora and fauna.

Even though no significant environmental effects have been reported, compared to the first HVDC links to be constructed modern sea electrode systems are designed with lower electric fields at the point of accessibility, ie outside the harbour wall or the outer surface of the active electrode element. Likewise design thresholds for step and touch potentials have fallen over time [43]. These changes have arisen through a lowering of the thresholds which are deemed acceptable, thus, designs that “avoided hazard” have been replaced with ones which “avoid annoyance” to humans and animals [21]. Additionally, anode materials with higher oxygen selectivity have become more widely used, hence reducing the quantity of chlorine and halogenated organic by-products generated.

It would appear that the onshore stray current issues experienced on the early links have largely been avoided on more recent links through a better understanding of the problem and vastly increased computational power to perform more detailed modelling studies during the design phase of the project, thereby preempting and addressing issues before they arise. Similarly, better underwater surveys combined with more detailed models can be used to predict if offshore metallic structures are likely to suffer corrosion. One limitation of these models today is a good understanding of the sub-seabed rock layers, specifically the electrical conductivity to be able to predict accurately the return current path through the sea and earth.

In the two of the three cases reported where HVDC subsea links were initially planned with sea electrodes, but later underwent design change to include a metallic return path, potential corrosion has been key driver for the change. As the seabed becomes more congested with infrastructure, it may become increasingly difficult for HVDC link developers to find cable routes and sea electrode locations which do not impact of third party assets. In an increasingly risk averse environment, third party asset owners may be less inclined to accept the installation of mitigation measures, such as sacrificial electrodes, preferring to press the HVDC subsea link developer to install a metallic return path.

Where these circumstances may arise, developers may choose to reduce project risk and delays (in public inquires or protracted discussions with third parties) by opting for bipoles or metallic returns from the start of the project. Particularly on interconnectors where energy trading is to take place the lost revenue from a delayed start may be outweighed by the additional cost of installing a metallic return. Similarly the risk of an ongoing liability for corrosion damage may be seen as too high by the HVDC link developer. Clearly, assessment of the risks and how to cost them will vary from project to project.

**10. CONCLUSIONS**

Of the approximately 40 HVDC subsea links in service today, 30% use sea electrodes as the return current path under normal or emergency operation. Sea electrodes provide a simple proven solution for the return current path having been used since the first HVDC subsea link in the 1950s. The engineering decision to adopt sea electrodes is complex and needs to weigh many elements including location, environmental impact, current capacity and financial factors (cost, flexibility, losses). All the environmental impacts studies of HVDC subsea links with sea electrodes have reported no significant effects caused during installation or many years of operation. The findings from these surveys and supporting research underpin the environmental impact assessments and statements for subsequent proposed projects, supplemented with locality specific information. In the few cases where the original proposed engineering solution was to adopt a sea return but the design has later been modified to use a metallic return path, concerns over potential corrosion of third party linear metallic structures have often driven this change.

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**REFERENCES**

1 G. Hjalmarsson, J. Thoren, U. Grape, G. Malmquist, R. Eriksson and M. Kvarngren, “After-service analysis of the 32 year old HVDC cable Gotland 1”, in *1992 International Council on Large Electric Systems (CIGRE) Sessions*, Paris, France, Paper 21-302, Aug. 1992.

2 “Subsea HVDC Connections”, available: <http://www.highvoltage.ecs.soton.ac.uk/>research/project.php?id=932

3 “List of HVDC projects with marine infrastructure”, available: [www.envirogulf.com/](http://www.envirogulf.com/)hvdc.html.

4 ABB website, “The Gotland HVDC power links”, available: <http://new.abb.com/systems/hvdc/>references/the-gotland-hvdc-link.

5 R. Rudervall, J.P. Charpentier and R. Sharma, “High Voltage Direct Current (HVDC) transmission systems technology review paper”, Energy Week 2000, Washington, D.C, USA, March 7-8, 2000.

6 J.F. Allaire, C.D. Clarke, G.L. Désilets, G. Moreau, L.R. Wilhelmsson, B.S.S. Ekehov and M.P. Garcia, “Leyte-Luzon HVDC power transmission: commissioning highlights, performance measurements and operating experience”, in 2000 International Council on Large Electric Systems (CIGRE) Sessions, Paris, France, Paper 14-101, Aug. 2000.

7 L-J. Zhao, H. Rao, X-L. Li, W. Zhang, Y. Xiang and M-L. Fu, “Development of ±160 kV XLPE Cable and its application to the world’s first three-terminal VSC HVDC system in China”, in 2014 Asia-Oceania Regional Council of CIGRE, Tokyo, Japan, Paper B1-1110, May 2014.

8 “HVDC Environmental Planning Guidelines”, International Council on Large Electric Systems (CIGRE) Technical Brochure 508, 2012.

9 “HVDC ground electrode design”, *Electric Power Research Institute (EPRI)*, report EL-2020, 1981.

10 E.W. Kimbark, *Direct Current Transmission,* Volume 1, London: John Wiley and Sons, 1971, Chapter 9.

11 C. Marchiori, “HVDC Monita project”, presented at the Region of Central and South East of Europe CIGRE event, Rome, Italy, Jan. 2014.

12 “The detailed spatial plan for transmission line corridor 400 kV with optical cable from Montenegrian coast to Pljevlja and submarine cable 500 kV with optical cable Italy-Montenegro”, *Montenegrin Ministry of Sustainable Development and Tourism (MMSDT)*, Jul. 2011.

13 “Labrador‐Island Transmission Link Environmental Impact Statement: Chapter 3 – Project Description”, Nalcor Energy, Apr. 2012.

14 “Maritime Link Environmental Assessment Report: Chapter 2 – Project Description”, EMERA Newfoundland and Labrador, Jan. 2013.

15 “2009 Annual Planning Report”, Transpower New Zealand Limited, 2009, Chapter 7.

16 G. Andersson and M. Hyttinen, “Skagerrak The Next Generation, HVDC and Power Electronic Technology System Development and Economics”, in *2015 International Council on Large Electric Systems (CIGRE) B4 Symposium*, Lund, Sweden, May 2015.

17 T.D. Ingemansson, T. Kiiveri, H. Nurminen, B.L. Pääjärvi 1 and K-G. Danielsson, “New Fenno-Skan 2 HVDC pole with an upgrade of the existing Fenno-Skan 1”, in *2012 International Council on Large Electric Systems (CIGRE) Sessions*, Paris, France, Paper B4-105, Aug. 2012.

18 “Compendium of HVDC schemes throughout the world”, *International Council on Large Electric Systems (CIGRE) Advisory Group B4.04*, 2005.

19 A. Nyman, B. Ekenstierna, H. Waldhauer, A. Persson, S. Nyberg, B. Drugge, D. Karlsson and J-O. Sjödin, “The Baltic Cable HVDC Project”, in *1996 International Council on Large Electric Systems (CIGRE) Sessions*, Paris, France, Paper 14-105, Aug. 1996.

20 “Technical Description Of Transpower’s Current Plans For Implementing The Proposal – Rev A: Inter-island HVDC Pole 1 Replacement Investigation/DC/Technical Description/001/Rev A”, Transpower New Zealand Limited, May 2008.

21 M.T. O’Brien, M. Zavahir, M. Clark and D. Boyle, “New Zealand bipolar HVDC earth/sea return operation – environmental experiences”, in *2006 International Council on Large Electric Systems (CIGRE) Sessions*, Paris, France, Paper B4-206, Aug. 2006.

22 “Basslink Draft Integrated Impact Assessment Statement Summary Report: Chapters 10 to 18”, NSR Environmental Consultants Pty Ltd, Jun. 2001.

23 L. Söderberg and B. Abrahamsson, “SwePol Link sets new environmental standard for HVDC transmission”, ABB Review, Apr. 2001.

24 M. Pompili and B.A. Cauzillo, “Innovative electrodes for HVDC submarine cables”, IEEE Trans. on Power Delivery, Vol. 31, pp1310-1316, 2016.

25 R.Rendina, M.R.Guarniere, R.Niccolai, G.Pazienza, A. Gualano, S.Malgarotti, A.Danelli, B.Jansson, F.Alvarez, W.Lovison, A.Persico, A.Orini, F.Bocchi, S.Aleo and G.Curtotti, “The realization and commissioning of the ±500 kV 1000 MW HVDC link Sardinia Island – Italian Peninsula (SAPEI)”, in *2012 International Council on Large Electric Systems (CIGRE) Sessions*, Paris, France, Paper B1-101, Aug. 2012.

26 W. Ruan, J. Ma., J. Liu, F.P Dawalibi and R.D. Southey, “Performance of HVDC ground electrodes in various soil structures”, in *2002 Proceedings of International Conference on Power System Technology (PowerCon)*, Kunming, China, Vol. 2, pp962-968, Oct. 2002.

27 “Compendium of HVDC schemes throughout the world”, *International Council on Large Electric Systems (CIGRE) Technical Brochure*, 003, 1987.

28 K. Tykeson, A. Nyman and H. Carlsson, “Environmental and geographical aspects in HVDC electrode design”, IEEE Trans. on Power Delivery, Vol. 11, pp1948-1954, 1996.

29 C. Di Mario, A. Giorgi, R. Guandalini, L. Mattiello, R. Niccolai, G. Pazienza, C. Pincella, M. Rebolini, R. Rendina and G. Simioli, “Environmental issues on the development of the new HVDC link Sardinia Island – Italian peninsula (SAPEI project)”, in *2012 International Council on Large Electric Systems (CIGRE) Sessions*, Paris, France, Paper B4-205, Aug. 2006.

30 M.R. Guarniere, A. Iliceto, M. Marzinotto and R. Niccolai, “HVDC link SA.CO.I.: operational experience and future developments”, in *2012 Proceedings of 8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER*), Cagliari, Italy, Oct. 2012.

31 “The influence of electric currents on marine fauna”, *International Council on Large Electric Systems (CIGRE),* Study Committee 10, 1959.

32 H. Westerberg, “Likströmskablar, ålar och biologiska kompasser (DC cables, eels and biological compasses)” (in Swedish), Fiskeriverkets Kustlaboratorium, 1999. Available: [www.balticcable.com/environindex.html](http://www.balticcable.com/environindex.html).

33 K. Faugstad, H. Borgen, N.H. Jendal, J.E. Skog and A. Strandem, “Experience from the licensing process for the North Sea HVDC interconnections. Possible consequences for future submarine links”, in *2002 International Council on Large Electric Systems (CIGRE) Sessions*, Paris, France, Paper 14-111, Aug. 2002.

34 L. Debus, “Elektrosmog im meer durch gleichsromerzeugte elecktrische und magnerische feldereine literaturstudie (Electrosmog in the sea by electric DC and magnetic fields)” (in German), *Deut. Hydro. Z. (German Journal of Hydrography)*, Suppl. 8, pp167-180, 1998.

35 A. Liljestrand, “Kontrollprogram bottenfauna, bottenflora (Inspection program: bottom flora and fauna) Baltic Cable” (in Swedish), Marin Miljöanalys AB, 1999. Available: [www.balticcable.com/environindex.html](http://www.balticcable.com/environindex.html).

36 L. Debus, H. Winkler and M.L. Zettler, “Vorläufige ergebnisse von felduntersuchungen an einer elektrode in der Ostsee (Preliminary results of field testing at an electrode in the Baltic Sea)”, in *Proceedings of Federal Agency for Nature Conservation Workshop, “Technische Eingriffe in marine lebensräume (Technical interference with marine habitats)”* (in German), Oct. 1999.

37 E. Andrulewicza, D. Napierskaa and Z Otremba, “The environmental effects of the installation and functioning of the submarine SwePol Link HVDC transmission line: a case study of the Polish Marine Area of the Baltic Sea”, *J. Sea Research*, vol. 49, pp337–345, 2003.

38 Whitehead, “Electric Field Measurements in Cook Strait (New Zealand) and Bass Strait (northern Tasmanian coast) in Relation to Elasmobranch Distribution”, in *Basslink Project – Final Environmental Impact Statement and Supplement to the Draft Integrated Impact Assessment Statement: Attachment D*, NSR Environmental Consultants Pty Ltd., Jun 2002.

39 “BC Hydro Vancouver Island Supply HVDC Reinforcement. Project Planning Report, Volume 2 Appendices”, Appendix J “HVDC sea return operation”, PM Report No. 0104, February 1997.

40 “Ecosystem Health of the Baltic Sea 2003–2007: HELCOM Initial Holistic Assessment”, Helsinki Commission Baltic Marine Environment Protection Commission, in *Balt. Sea Environ. Proc. No. 122.*, 2010.

41 “Labrador‐Island Transmission Link Environmental Impact Statement: Chapter 10 – Existing Biophysical Environment”, http://new.abb.com/systems/hvdc/references/swepol-link.

42 “Labrador‐Island Transmission Link Environmental Impact Statement: Chapter 14 – Marine Environment: Environmental Effects Assessment”, Nalcor Energy, Apr. 2012.

43 “General Guidelines for the Design of Ground Electrodes for HVDC Links”, *International Council on Large Electric Systems (CIGRE)* SC14.21 – TF2, 1998.

44 “Labrador‐Island Transmission Link Environmental Assessment: Marine Environment and Effects Modelling Component Study”, Nalcor Energy, Nov. 2011.

45 B. Abrahamsson, L. Soderberg and K. Lozinski, “SwePol HVDC Link”, in *2001* *Seventh International Conference on AC-DC Power Transmission (IEE Conf. Publ. No.485),* London, UK, pp211-13, Nov. 2001.

46 “Final Environmental Impact Statement and Supplement to the Draft Integrated Impact Assessment Statement Summary Report”, NSR Environmental Consultants Pty Ltd, Jun. 2002.

47 A. Ardito, C. Pincella, G. Simioli, G.P. Stigliano, L. Camilli, C. Di Mario, M. Rebolini, D. Tagliatesta, A. Giorgi, G. Pazienza and R. Rendina, “Feasibility of a new long distance submarine HVDC link between Sardinia Island and Italian peninsula (SAPEI)”, in *2004 International Council on Large Electric Systems (CIGRE) Sessions*, Paris, France, Paper B4-206, Aug. 2004.



Figure 1 – Number of HVDC subsea links commissioned since the 1950s and cumulative total of commissioned projects to the end of 2015.



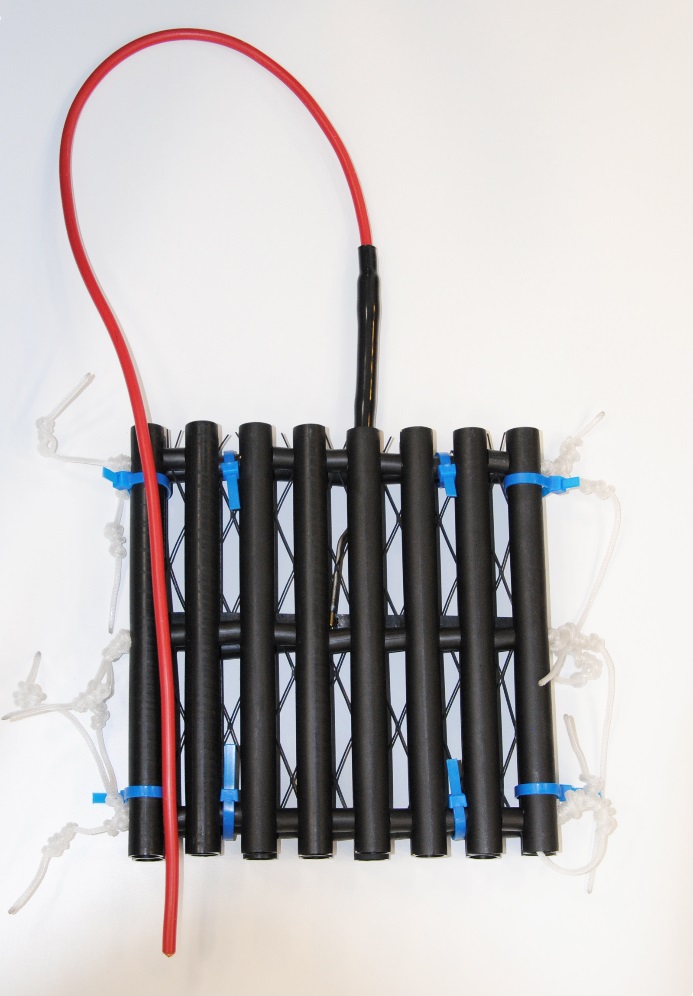


Figure 2 – Photo of Sansum Narrows pond electrode (Top) on Vancouver Island, Canada; the 28 individual electrode elements can be seen arranged along the 100 m retaining berm wall (photo courtesy of BC Hydro). Sample of coated titanium mesh electrode (Lower) sandwiched between two layers of protective plastic tubing (photo courtesy of Fingrid Oyj).



Figure 3 – Proportion of installed HVDC subsea cable projects with and without sea electrodes, and breakdown of the type of electrode system.



Figure 4 – Evolution of sea electrode current carrying capacity; the plot includes data for the originally declared commission capability and subsequent upgrades.



Figure 5 – Relationship between HVDC subsea connection length and transfer capacity for links with sea electrode systems (solid diamonds) and without sea electrodes (open circles).

| **Project** | **Location Converter Stations** | **Year of installation** | **Subsea length**  **(km)** | **Rating**  **(MW)** | **Voltage**  **(kV DC)** | **Electrode Current**  **(A DC)** | **Grounding Electrodes** | **Electrode Material** | **Polar type / Operation** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Europe*** | | | | | | | | | |
| **Gotland 1**  Sweden | Ygne - Vastervik (SV) | 1954 to 1986 Dismantled | 96 | 30 | 150 | 914 | One pond and one marine electrode | Magnetite/linseed impregnated graphite, copper | 1 cable/monopole |
| **Gotland 2 & 3**  Sweden | Ygne - Vastervik (SV) | 1983 (G2), 1986 (G3) | 90 | 260 | ±150 | 910 | Two pond electrodes | Magnetite | 2 cables/bipolar mode |
| **Konti-Skan 1**  Sweden - Denmark | Stenkullen (SE) - Vestor Hassing (DK) | 1965 to (Replaced 2006) | 87 | 250 | 250 | 1050 | One shore and one marine electrode | Graphite/coke, copper | 1 cable/monopole |
| **Konti-Skan 1 &2**  Sweden - Denmark | Lindome (SE) - Vestor Hassing (DK) | 1988 KS-1 upgraded in 2006 | 88 | 380 (KS1) + 300 (KS2) | ±285 | 1350 | One shore and one marine electrode | Graphite/coke  Original cathode replaced | 2 cables/bipolar mode |
| **SACOI**  Italy – France - Italy | Codrongianos (IT) - Lucciana (FR) - Suvereto (IT) | 1967, 1986, 1992 | 119 | 300 | ±200 | 1500 | Two marine and one land electrode | Copper, coated titanium, silicon-iron alloy | 2 cables/monopole |
| **Skagerrak 1&2**  Norway - Denmark | Kristiansand (NO)- Tjele (DK) | 1976, 1977 | 124 | 500 | 250 | 1000 | Two shore electrodes | Graphite/coke | 2 cables/bipolar mode |
| **Skagerrak 3** (SK3)  Norway - Denmark | Kristiansand (NO) - Tjele (DK) | 1993 | 124 | 500  (Total 1000) | 350 | 1000 | Two shore electrodes | Graphite/coke | 1 cable – operated as bipole with SK1 & 2 as monopoles |
| **Skagerrak 4** (SK4)  Norway - Denmark | Kristiansand (NO) - Tjele (DK) | 2015 | 137 | 700  (Total 1700) | 500 | 1000 | Two shore electrodes | Graphite/coke | 1 cable - bipole with SK3. SK1 & 2 also bipolar mode |
| **Fennoskan 1**  (FS1) Sweden - Finland | Dannebo (SE) - Rauma (FI) | 1989 | 200 | 500 | 400 | 1280 | Two marine electrodes | Coated titanium, copper | 1 cable/monopole |
| **Fennoskan 2**  Sweden - Finland | Dannebo (SE) - Rauma (FI) | 2011 | 200 | 800  (Total 1300) | ±500 | 1700 | Two marine electrodes | Coated titanium | Formed bipole with FS1 |
| **Baltic Cable**  Sweden - Germany | Kruseberg (SE) – Lubeck Herrenwyk (DE) | 1994 | 250 | 600 | 450 | 1364 | Two marine and one land electrode | Coated titanium, copper, coated titanium | 1 cable/monopole |
| **Kontek**  Denmark - Germany | Bjaeverskov (DK) - Bentwisch (DE) | 1995 | 52 | 600 | 400 | 1500 | Two marine electrodes | Coated titanium, copper | 1 cable/monopole |
| **GrIta**  Greece - Italy | Galatina (IT) Arachthos (GR) | 2001 | 163 | 500 | 400 | 1250 | One pond and one marine electrode | Coated titanium, copper | 1 cable/monopole |
| **SAPEI**  Italy | Flume Santo - Latina (IT) | 2010 | 420 | 1000 | ±500 | 2500 | One pond and one marine electrode | Coated titanium, copper | 2 cables Pole 1 (2009) Pole 2 (2010) Bipole |
| **\*MonIta**  Montenegro - Italy | Villanova (IT) - Tivat (ME) | 2017 | 390 | 1200 | ±500 | 1200 | Two marine electrodes | Coated titanium, copper | 2 cables/bipolar mode |
| ***North America*** | | | | | | | | | |
| **Vancouver 1 & 2**  Canada | Delta - North Cowichan (CA) | 1968, 1977 | 33 | 682 | +260/‑280 | 1800 | One pond and one shore electrode | Graphite, silicon-iron/coke | 2 cables/bipolar mode |
| **\*Labrador Island Link (LIL)**  Canada | Muskrat Falls – Soldiers Pond (CA) | 2016 | 32 | 900 | ±350 | 1286 | Two pond electrodes | Silicon-iron | 3 cables/bipolar mode |
| **\*Maritime Link**  Canada | Bottom Brook – Woodbine (CA) | 2017 | 180 | 500 | ±250 | 1250 | Two pond electrodes | As yet unknown | 2 cables/bipolar mode |
| ***Asia Pacific*** | | | | | | | | | |
| **Inter-Island** **1** (II1)  New Zealand | Haywards – Benmore (NZ) | 1965-1991 | 42 | 600 | ±250 | 1200 | One shore and one land electrode | Mild steel/coke, silicon-iron/coke | 2 (+1) cables / bipolar mode |
| **Inter-Island** **2** (II2)  New Zealand | Haywards – Benmore (NZ) | 1993 (upgrade) | 42 | 1240, later 1040 | -350 | 2400 | One shore and one land electrode | Mild steel/coke, silicon-iron/coke | New cables. New II2 convertor operates as bipole with reconfigured upgraded II1 |
| **Inter-Island** **3** (II3)  New Zealand | Haywards – Benmore (NZ) | 2013 (replacement to Pole 1) | 40 | 1000, later 1200 | 350 | 2400 | One shore and one land electrode | Mild steel/coke, silicon-iron/coke | New II3 convertor operates as bipole with II2 |
| **Leyte - Luzon**  Philippines | Ormoc – Naga (PH) | 1997 | 21 | 440 | 350 | 1260 | Two beach electrodes | Silicon-iron/coke | 1 cable, 1 spare bipolar mode |
| **Haenam - Cheju**  South Korea | Haenam – Cheju (KR) | 1998 | 100 | 300 | ±180 | 834 | Two marine electrodes | Aluminium alloy | 2 cables/bipolar mode |

Table 1 – Details of past, present and future HVDC subsea cable links with sea electrode systems.

\* Projects currently in delivery



|  |  |  |  |
| --- | --- | --- | --- |
|  | **L’Anse au Diable (LIL)** | **Dowden’s Point (LIL)** | **Tasmania (Basslink)** |
| **Normal operation** | 4.59 x 10-6 g/l/day | 4.96 x 10-5 g/l/day | 0.083 – 0.277 mg/m2/s |
| **Emergency operation** | 6.89 x 10-4 g/l/day | 7.44 x 10-3 g/l/day |  |

Table 3 – Predicted chlorine emissions from the sea electrode given in the Environmental Impact Statements for the Basslink and Labrador Island Link (LIL).