HVDC Subsea Cable Electrical Return Path Schemes: Use of Sea Electrodes and Analysis of Environmental Impact

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About HubNet

HubNet is a consortium of researchers from eight universities (Imperial College and the universities of Bristol, Cardiff, Manchester, Nottingham, Southampton, Strathclyde and Warwick) tasked with coordinating research in energy networks in the UK. HubNet is funded by the Energy Programme of Research Councils UK under grant number EP/I013636/1.

This hub will provide research leadership in the field through the publication of in-depth position papers written by leaders in the field and the organisation of workshops and other mechanisms for the exchange of ideas between researchers and between researchers, industry and the public sector.

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- Design of smart grids, in particular the application of communication technologies to the operation of electricity networks and the harnessing of the demand-side for the control and optimisation of the power system.
- Development of a mega-grid that would link the UK's energy network to renewable energy sources off shore, across Europe and beyond.
- Research on how new materials (such as nano-composites, ceramic composites and graphene-based materials) can be used to design power equipment that are more efficient and more compact.
- Progress the use of power electronics in electricity systems though fundamental work on semiconductor materials and power converter design.
- Development of new techniques to study the interaction between multiple energy vectors and optimally coordinate the planning and operation of energy networks under uncertainty.
- Management of transition assets: while a significant amount of new network equipment will need to be installed in the coming decades, this new construction is dwarfed by the existing asset base.
- Energy storage: determining how and where storage brings value to operation of an electricity grid and determining technology-neutral specification targets for the development of grid scale energy storage.

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Contents

1. Introduction ........................................................................................................................................ 1
   1.1 Global HVDC subsea connections ............................................................................................. 1
   1.2 Methods to provide an electrical return path ............................................................................. 2
      1.2.1 Bipole ................................................................................................................................... 2
      1.2.2 Metallic return ...................................................................................................................... 2
      1.2.3 Ground electrodes ................................................................................................................ 2
      1.2.4 Sea electrodes ...................................................................................................................... 2
      1.2.5 Hybrid systems .................................................................................................................... 3
   1.3. Global practice ............................................................................................................................ 3

2. CIGRE reports ..................................................................................................................................... 4
   2.1 Compendium of HVDC schemes throughout the world ............................................................ 4
   2.2 HVDC Environmental Planning Guidelines .............................................................................. 4
      2.2.1 Electric field ......................................................................................................................... 4
      2.2.2 Transformer saturation ......................................................................................................... 5
      2.2.3 Electrolysis products .......................................................................................................... 5
      2.2.4 Magnetic field ...................................................................................................................... 5
      2.2.5 Site selection ....................................................................................................................... 6
      2.2.6 Construction ....................................................................................................................... 6
      2.2.7 Environmental experience .................................................................................................. 6
   2.3 General guidelines for HVDC electrode design ........................................................................ 6

3. HVDC links and sea electrodes ........................................................................................................ 7
   3.1 Europe .......................................................................................................................................... 7
      3.1.1 Baltic Sea region .................................................................................................................... 7
         3.1.1.1 Gotland ............................................................................................................................ 7
            3.1.1.1.1 Gotland 1 .................................................................................................................. 7
            3.1.1.1.2 Gotland 2 and 3 ....................................................................................................... 8
         3.1.1.2 Konti-Skan ...................................................................................................................... 8
            3.1.1.2.1 Monitoring .............................................................................................................. 8
         3.1.1.3 Skagerrak ........................................................................................................................ 9
            3.1.1.3.1 Skagerrak 1 & 2 ........................................................................................................ 9
            3.1.1.3.2 Skagerrak 3 .............................................................................................................. 9
            3.1.1.3.3 Skagerrak 4 .............................................................................................................. 9
            3.1.1.3.4 Monitoring .............................................................................................................. 10
3.2 Asia Pacific .............................................................................................................. 18
  3.2.1 Haenam – Jeju Korea ......................................................................................... 18
  3.2.2 Leyte – Luzon Philippines ................................................................................. 18
  3.2.3 Inter-Island New Zealand .................................................................................. 19
    3.2.3.1 Monitoring ..................................................................................................... 20
      3.2.3.1.1 Corrosion .................................................................................................. 20
      3.2.3.1.2 Interactions with AC networks ................................................................. 21
      3.2.3.1.3 Interactions with humans ......................................................................... 21
      3.2.3.1.4 Interactions with animals ........................................................................ 22
      3.2.3.1.5 Interactions with marine life ................................................................. 22
  3.2.4 Basslink Australia .............................................................................................. 22
    3.2.4.1 Proposed electrode design ........................................................................... 23
    3.2.4.2 DIAS evidence to support the use of sea electrodes ................................. 23
      3.2.4.2.1 Construction phase ................................................................................. 23
      3.2.4.2.2 Electric fields .......................................................................................... 24
      3.2.4.2.3 Magnetic fields ....................................................................................... 24
      3.2.4.2.4 Electrolysis products .............................................................................. 25
      3.2.4.2.5 Fisheries .................................................................................................. 27
      3.2.4.2.6 Heat generation ....................................................................................... 27
1. Introduction
This paper includes a review of all installed High Voltage Direct Current (HVDC) schemes worldwide that utilise sea electrodes to provide an electrical return path. Analysis of the environmental impact of the schemes is also summarised. All HVDC subsea cable connections are effectively unique and consequently the impact of a particular design for a given location requires specific analysis and assessment. However with the increasing number of schemes worldwide it is now possible to draw general conclusions about the relative merits of the use/incorporation of sea electrodes not just in terms of operational considerations but also in terms of any environmental impact.

1.1 Global HVDC subsea connections
There are almost 40 HVDC subsea connections in service worldwide (see Appendix A) with yet more projects in delivery: this list (correct at the end of 2015) is based on a review, revision and updating of the information compiled by [Balloch]. This number has grown in the last few years due to a variety of reasons including:

1. Liberalisation of the electricity market in Europe – this has seen a big increase in the number of inter-country subsea links being installed to trade electricity across the continent. This rapid growth in the number of HVDC subsea connections additionally increases the security of supply and in the future potentially allows renewable electricity to be transported from regions of high generation to regions of high demand more efficiently, or moved to regions where the electricity can be stored in large pumped hydro facilities.
2. Security of supply – in other parts of the world subsea HVDC links are being installed to connect islands in the adjoining mainland or interconnect groups of islands. This helps meets customers’ demands for more reliable electricity and often allows old inefficient/costly generating equipment on the islands on be run less frequently thereby reducing CO2 emissions.
3. New technology – the introduction of VSC convertor station technology and the rapid evolution in its maximum operating voltage has improved the economic viability of HVDC links.

In addition to these changing drivers there is a trend towards longer links carrying higher loads, which presents new challenges for the HVDC system design and integration into the AC network. Every HVDC connection is unique and designed taking many factors in to account [CIGRE 2012] including:

- Length
- Power transfer
- Losses
- One way or two way power flow
- Reliability
- Black start capability

These fundamental design choices affect both the design of the convertor systems and subsea components. In an HVDC system the power must flow from the convertor
station sending the electricity to the receiving convertor station and back again. It is the
manner in which the electricity returns which is the focus of this position paper.

1.2 Methods to provide an electrical return path
The following section briefly describes the different types of return path [CIGRE 2012]
[EPRI][Kimbark].

1.2.1 Bipole
The HVDC cable system comprises of two identical high voltage subsea cables
connecting the sending and receiving convertor stations; one operating with positive
polarity and the other negative polarity. The return current flows through the high
voltage cable running from the receiving convertor back to the sending convertor.

1.2.2 Metallic return
The HVDC system comprises of a single HVDC cable to transmit the electricity from the
sending to receiving convertor but typically uses a medium voltage (20 kV) cable to
carry the return current. The medium voltage conductor can either be laid in a separate
trench or bundled with HVDC cable. A more recent development involves integrating
the medium voltage metallic return into the HVDC cable design.

1.2.3 Ground electrodes
HVDC systems with ground electrodes have no metallic return path for the current but
rather transmit the current through the earth between arrays of electrodes at either end
of the link. These electrodes are buried up to 500 m deep, although 50-100 m is more
typical. This design is not common for subsea cable systems (since the sea provides a
better electrical path) and requires favourable geological conditions to carry the return
current. Traditionally, this method has been used for long distance overhead HVDC
transmission on land.

1.2.4 Sea electrodes
As with ground electrodes, sea electrode systems do not have a continuous metallic
connection for the return current, rather the system uses the inherent conductivity of
the salt water to carry the electrical current: in practice much of the current flows
depthily through the earth. There are three typical sea electrode installation types:

1. Shore – An array of electrodes are installed on land, often buried below the
   beach, and consequently in contact with salt water.
2. Pond – An electrode array is installed in a man-made lagoon/harbour. The sub-
   electrodes typically hang from a pontoon in the salt water.
3. Marine – An array of electrodes are typically installed on the sea bed. The
   cathode is often a bare copper conductor installed in a ring or linear
   configuration.

The electrode material varies depending on the electrode polarity and installation
environment/design (water circulation, current density or voltage gradient limits etc).
Cathodes can be made from bare copper conductor or graphite rods (surrounded by
coke). Anodes can be made from graphite rods (surrounded by coke), titanium rods or
nets sometimes functionalised with noble earth elements, or certain varieties of silicon-
irons.
1.2.5 Hybrid systems
Since subsea HVDC cables are prone to damage, for example from anchors or fishing gear, designers may include a sea electrode in a bipole or metallic return design. The former situation can arise when an existing monopole with sea electrodes is later upgraded to a bipole with the addition of another HVDC cable. The sea electrodes are not in use under normal operation but if one of the bipole cables is out of service the system can be reconfigured as a monopole with the sea electrode providing the return path: this allows half the bipole power to be transferred until the damaged cable is repaired. Similarly if the metallic return is damaged the sea return can ensure continued power transfer.

1.3. Global practice
Presently approximately 30% of installed subsea HVDC links use sea electrodes either under normal or emergency operation (see Appendix B): this list is based on a review, revision and updating of the information compiled by [Balloch]. These electrode systems have been installed since the earliest subsea HVDC links were built and are still being designed and installed today. The decision to choose a sea electrode system is a balance of many factors including:

1. Financial considerations – A long metallic return is costly due to both the investment in the copper conductor and its installation in the seabed. Sea electrode systems are economically attractive for long HVDC subsea links.
2. Lower losses – The electrical resistance of the return path through the sea and sub-seabed layers is lower than a metallic return. This leads to lower electrical losses on the link, potentially lowering the life cycle cost compared to installing a metallic return cable.
3. Increased flexibility for bipoles – Although bipoles do not require a separate sea return path during normal operation, installation of a sea electrode system allows the link to operate at 50% capacity in the event of a cable fault.
4. Environmental considerations – The design of any sea electrode system has to take account of the impact of the electric and magnetic fields generated, and electrolysis products produced on the environment.
5. Corrosion considerations – The return path current can cause electrolytic corrosion of nearby metallic structures. Modelling studies are required to assess the impact and determine mitigation measures.
6. Location – In some cases a suitable site to install a sea electrode system may not be available close to the HVDC cable route.

In this paper, Section 2 provides a brief summary of the studies CIGRE has published on HVDC practices pertinent to subsea cables. Section 3 gives an overview of each HVDC project installed with a sea electrode including a brief history, technical details of the connection and specifically the electrodes, and information on any environmental monitoring which has taken place. All the sources reviewed refer to steady state design parameters (eg. current density or field gradient) under normal operating conditions: no specific information was found for the transient performance of the electrode system under fault conditions. Section 3 also includes details of three projects which were initially conceived with sea electrodes but ultimately were built without them.
2. CIGRE reports

The Council on Large Electric Systems (CIGRE) is an international non-profit association of experts (utilities, manufacturers, consultants, researchers, testing bodies etc) from around the world to share their knowledge and experience. A major part of CIGRE’s activities is developing reports summarising state-of-the-art information on particular topics of industry interest. CIGRE’s involvement in reporting the environmental impacts of sea electrodes stretches back more than 50 years [CIGRE 1959].

2.1 Compendium of HVDC schemes throughout the world

In 1987 Study Committee 14 published the first major CIGRE document covering global HVDC projects, “Compendium of HVDC schemes throughout the world” [CIGRE 1987]. This document, Technical Brochure 003, compiled technical data on all the existing HVDC schemes at the time, many of which are still in operation today. In 2005 the review was updated [CIGRE 2005] although no technical brochure was published.

2.2 HVDC Environmental Planning Guidelines

The purpose of CIGRE Technical Brochure 508 is, “to provide an overview of the environmental issues to be considered in the technical design and environmental approval processes associated with an HVDC system”. The brochure [CIGRE 2012] focuses on possible environmental impacts related to different HVDC concepts and the various components which make up the total HVDC solution; the brochure goes on to address potential mitigation measures. Published in 2012, the content benefits from the knowledge gained from the many HVDC projects delivered during the 1990s and early 2000s. Chapter 6 of Technical Brochure 508 specifically addresses HVDC electrodes (land and sea). The following section is a brief summary of the contents of that chapter.

Since all HVDC projects are unique it is hard to generalise on the impact of any individual electrode system or the factors which lead developers to opt to install an electrode system. However, in coming to a particular decision all the following need to be considered during the scoping/planning process:

- Electric fields
- Transformer saturation
- Electrolysis products in the sea
- Magnetic fields
- Site selection
- Construction

2.2.1 Electric field

The electric field between the electrodes causes a current to flow, the distribution and magnitude depends on the local resistivity of the sea and bedrock layers. Current can also flow in nearby metallic (low resistivity) objects, such as pipelines and cables, particularly if they align with the field direction causing corrosion where the stray current leaves the object; corrosion occurs when the current exceeds known material specific critical values.

The current distribution can be predicted using three dimensional finite element models and experience shows that issues can be planned for and cost effectively mitigated.
Often this is simply a case of installing the electrode further from the metallic objects, or adding more material to a sacrificial anode connected to a pipeline. New pipelines can be fitted with insulating joints. Additional cathodic protection or impressed current systems can also be installed.

### 2.2.2 Transformer saturation

Although not an environmental impact, transformers located close to an electrode can suffer from saturation of the core due to current entering through the grounded star neutral point. This problem can be mitigated by ensuring there is sufficient distance between the electrode and nearby transformers, or installing blocking resistors into the neutral connection.

### 2.2.3 Electrolysis products

Electrolysis is a consequence of the electrical current flowing through the seawater. At the anode two competing reactions take place generating oxygen (from the water molecules) and chlorine (from the salt in the water). Hydrogen is liberated at the cathode.

Chlorine is unstable in seawater reacting to form hypochlorite and in turn, chloride and chloroform; bromide present in seawater also forms bromine and similarly hypobromite, bromide and bromoform. Chloride and bromide are naturally occurring and considered harmless. Chloroform and bromoform are intrinsically toxic, however, bromoform is produced by certain algae and is the dominant organo-halide in natural seawater.

Mitigation involves controlling the ratio of oxygen to chlorine produced at the anode by:

1. Carefully selecting the anode material,
2. Maintaining a low local pH,
3. Reducing the current density.

To date, studies monitoring marine flora and fauna near sea electrodes have raised no environmental concerns caused by the electrolysis products.

### 2.2.4 Magnetic field

Magnetic fields in the sea are generated by the current in the HVDC cable, current in the electrode array cable (if it is a marine electrode) and the current flowing between the two electrodes. All three can under the right circumstances cause magnetic compass deviation; typically in shallow water and very close to the cables or electrode array. Local regulations often specify the maximum permissible deviation. In the case of monopoles with marine electrodes one mitigation strategy is to install the electrode array cable parallel and close to the HVDC cable thereby causing the opposing magnetic fields to cancel partially each other.

Some fish species use the earth’s magnetic field to navigate during migration, such as eels and salmon travelling between the Baltic Sea and Atlantic Ocean. Studies monitoring of their movements have shown insignificant changes in behaviour.
2.2.5 Site selection
The key factors for sea electrode location are:

1. Good electrical conductivity in the vicinity of the electrode, both in the water and more critically in the deeper ground layers.
2. Good water exchange around the anode to control electrolysism products.
3. Sheltered location to minimise wave or current damage to the electrode.

Additionally it is important that the electrodes be accessible for inspection, maintenance and repair which tends to favour installation in shallow (typically ~10 m) water.

2.2.6 Construction
Environmental considerations during the construction phase of the project are no different for the electrode system to other assets. Sea electrodes need to be connected to the shore and onward to the convertor station, thus not all impacts are exclusively confined to the marine environment. The major construction considerations are:

1. Damage to historic sites or archaeological remains.
2. Noise during excavation and civil works. This can impact both local residents but consideration also has to be given to marine creatures during the installation of sea electrodes.
3. Runoff and sedimentation caused during excavation.
4. Habitat disturbance to flora and fauna at the electrode installation site and along the route connecting the electrode to the convertor station.

Ring or star electrodes are often buried up to four metres deep and can measure close to one kilometre across; consequently the trenching involved during installation can be extensive. Shore-based or shoreline electrode arrays are much more compact although the latter can require the construction of a dam or breakwater. Mat-type sea electrodes are often laid on the seabed and protected with rocks or when bare copper conductor is used raised above the sea floor to prevent burial; both types of sea electrode impact a small area of seabed.

2.2.7 Environmental experience
It may either be a requirement of the planning consent or a voluntary activity to instigate an environmental monitoring programme before and after commissioning an HVDC link to assess any changes that occur.

The CIGRE technical brochure briefly summarises the conclusion of environmental monitoring studies on the following projects; Baltic Cable, Kontek, Konti-Skan, New Zealand link and Skagerrak. Details of these individual monitoring studies are given in the following project specific sections, however the CIGRE report concludes "no measureable environmental impact from sea electrodes effects have been found".

2.3 General guidelines for HVDC electrode design
CIGRE Working Group B4.61 “General Guidelines for HVDC Electrode Design” is currently finalising work on a technical brochure focussed on HVDC electrode design. The work was due to be published in 2013, but is now expected in 2016. The terms of reference for this Working Group can be summarised as:
1. Review of global HVDC schemes, electrode configurations, and modes of operation. The work will also update CIGRE's 2006-2007 survey on operational experience of installed electrode stations and designs of auxiliaries and monitoring systems. The impact of electrode design on the reliability of the HVDC system will also be addressed.

2. Develop electrode design criteria including electrode duty, safety, polarity, electrical interference, corrosion impacts, and electrolysis emissions. The Technical Brochure will also review the process of site selection.

3. Technology update on electrode station study and design, including:
   a. Geological modelling scenarios – resistivity measurement technologies for earth and water, field programs to collect data, and definition of extents of geological units to be modelled
   b. Electrical field simulations – modelling the electrode in the earth and/or sea, and interpretation of the outputs
   c. Electrode design processes – design examples and data for environmental impact assessments including electrical interference, corrosion impact and simplified electrolysis emission analysis.

4. Consider design issues such as electrode line termination and integration into electrode installations, as well as, auxiliary systems for electrode stations.

5. Review testing and commissioning practices, and additionally, operation and maintenance including possible instrumentation monitoring.

3. HVDC links and sea electrodes

This section compares the various schemes that employ sea electrodes to provide an electrical return path. The comparison is organised into three geographical areas, namely Europe (12 schemes), Asia Pacific (4 schemes) and North America (3 schemes).

3.1 Europe

The following discussion of subsea HVDC links in Europe with sea return systems is divided into two main sections, namely, the Baltic Sea and Mediterranean, since projects within these regions have many commonalities. The ongoing Monita link is also discussed, as well as the NorNed link which was originally planned with sea electrodes but ultimately was delivered as a bipole.

3.1.1 Baltic Sea region

3.1.1.1 Gotland

The world’s first subsea HVDC link was commissioned in 1954 between Vastervik on the Swedish mainland and Ygne on the island of Gotland: the subsea cable was 90 km long.

3.1.1.1.1 Gotland 1

The original 100 kV 20 MW monopolar connection (Gotland 1) was subsequently upgraded to 150 kV 30MW in 1970 with the implementation of new thyristor valve convertor stations [ABB]. As the first link of its kind all aspects of the design were groundbreaking; the sea return system comprised of a marine cathode and coastal pond anode. The cathode was a bare 120 mm² copper conductor approximately 350 m offshore. The original anode comprised 12 magnetite elements suspended from a
platform in a brackish water pool retained by a rock barrier [EPRI][Hjalmarsson]. In 1967 the anode elements were upgraded to linseed impregnated graphite. At full capacity (200 A) the current density was 0.42 A/m² and the electrode elements had a life of 2-3 years. No corrosion problems with stray currents were reported. This connection was decommissioned in 1986 when Gotland 3 came into service.

3.1.1.1.2 Gotland 2 and 3
In 1983 an additional monopole, Gotland 2, was added between Vastervik and Ygne. The new 92 km 150 kV 130 MW connection operated independently of Gotland 1. The additional transfer capacity from the mainland allowed an old oil-fired power station and diesel generators in Visby to be only operated for emergency power [ABB].

Gotland 3 was added in 1986 and was paired with Gotland 2 to form a ±150 kV 260 MW bipole. At the same time Gotland 1 was decommissioned after 30 years in service. The new bipole uses a shore-based pond electrodes protected by breakwaters, with each containing 48 magnetite electrode elements capable of carrying 910 A [CIGRE 2005].

3.1.1.2 Konti-Skan
Konti-Skan 1 (KS1), commissioned in 1965, was a 250 MW ±250 kV monopole link between Denmark and Sweden containing two subsea sections joined by an overhead line running across the Danish island of Laesoe; 23 km from the Danish mainland to Laesoe and 64 km from Laesoe to Sweden [CIGRE 1987, 2005]. A second connection, Konti-Skan 2 (KS2), 300 MW ±285 kV, was added in 1988 from Lindome on the Swedish side to Vester Hassing.

KS1 was installed with a shore based 1000 A shoreline electrode (anode) at Soera (Denmark). The site was chosen due to wet ground conditions; the electrode is situated at the coast approximately 20 m inland. The risk of corrosion was deemed low with no uninsulated cable networks or pipes in the vicinity [EPRI]. Details of the anode design parameters and calculations are given in [Kimbark]. The original marine cathode 3 km offshore from Risø in Sweden consisted of 300 m of bare 600 mm² copper conductor [EPRI].

With the addition of KS2, the link became bidirectional (although remained homopolar) consequently the original cathode station in Sweden was modified to operate as either an anode or cathode [CIGRE 2005]. Both KS1 and KS2 poles share the same 1350 A graphite-based electrodes:

- In Denmark the electrode comprises 25 vertical graphite electrodes at 5 m intervals connected in parallel (the end three electrodes are spaced at 3 m and 4 m for field control); each is placed in a wooden structure backfilled with coke backfill [CIGRE 2005][Ruan]. Step voltage measurements revealed a maximum value of 2.0 V near the ends of the electrode array on land and 0.3 V in the sea: these are respectively lower and higher than calculations by Ruan et al [Ruan].
- The Swedish electrode is approximately 3 km offshore and consists of 30 graphite electrodes on the seabed at a depth of 7-10 m; each electrode is contained in glass-fibre sacks filled with coke [CIGRE 2005].

3.1.1.2.1 Monitoring
The presence of benthic fauna on and around the graphite electrodes whilst in operation has been investigated using video recording. It was discovered that organisms, such as crabs and starfish, live directly on the electrodes seemingly without any deleterious effect [Nielsen cited in Faugstad]. Furthermore, fish observed close to the electrodes were not seen to react to the electric field estimated to be approximately 6 V/m [Faugstad].

3.1.1.3 Skagerrak
Connecting Norway and Denmark across the Skagerrak Strait, the Skagerrak interconnection has a long history. The original Skagerrak 1 & 2 bipole rated at ±250 kV 500 MW was commissioned in 1976-77. An additional 350 kV 500 MW connection, Skagerrak 3, was added nearly 20 years later. A further 20 years passed before Skagerrak 4 (500 kV 700 MW) was added. The evolving configuration of the Skagerrak interconnection with the addition of each successive pole is detailed in [Andersson].

3.1.1.3.1 Skagerrak 1& 2
Skagerrak 1 & 2 was designed with shore electrodes at Lovns Bredning (Denmark) and Kristiansand (Norway); these can operate as cathode or anode. Experience gained from the Konti-Skan project (Sweden – Denmark) fed into the electrode design.

In Denmark the electrode site was chosen because of its isolated location and good local ground conductivity conditions. The electrode has 41 parallel connected graphite electrodes; these are arranged in 0.6 m deep concrete rings 2.5 m in diameter and filled with coke. These are spaced 8 m apart along the shoreline with an extra element at the end plus an additional element 20 m in front [CIGRE 1987, 2005][EPRI]. The electrode units are buried two metres deep corresponding to approximately 0.6 m below the local water table. The array is designed with an average current density of 32.3 A/m² and the maximum voltage gradient at 1000 A is 12 V/m. Following commissioning a decision was made to double the number of electrodes due to high voltage gradient measurements caused by higher than expected ground resistance.

In Norway the electrode is designed in a similar manner except that the graphite electrodes are placed in a wooden structures with coke backfill. There are 61 electrodes in total; some of these are connected in series to give better current distribution.

3.1.1.3.2 Skagerrak 3
No modification was made to the sea electrode system with the addition of Skagerrak 3. Nevertheless modifications were made to Skagerrak 1 & 2; the original bipole was reconfigured to two monopoles. SK1 & 2 were then configured as a bipole with SK3 (opposite polarity to SK1 & 2). Due to the different convertor current ratings the pole currents were not always balanced, particularly during high power transfer, in which case the imbalanced current passed through the sea electrode system. Even at the greatest possible mismatch (SK1 & 2 1000A, SK3 1430 A) the sea current remained lower than the original SK1 & 2 electrode design ratings with one cable out of service [Strandem][Andersson].

3.1.1.3.3 Skagerrak 4
SK1, 2 and 3 were once again reconfigured with the addition of SK4. SK1 & 2 reverted to the original bipole configuration, and a new bipole created from SK3 and SK4. The convertor current ratings of SK3 & 4 almost balance; only a 30 A difference at maximum power transfer. Consequently the current flowing through the sea electrode system under normal operation was reduced to almost zero [Andersson].

3.1.1.4 Monitoring
Sediment samples from the vicinity of the graphite/coke anode and a remote reference location have been analysed for chlorine and halogenated compounds [Faugstad]. No negative environmental impact was discovered.

3.1.1.4 Fenno-Skan
In 1989 the 500 MW ±400 kV Fenno-Skan 1 monopole cable between Sweden and Finland was commissioned [CIGRE 2005]. The connection used sea electrodes with:

1. A cathode at the Finnish end of the link consisting of a 1500 m x 700 m loop of bare 300 mm² copper conductor and,
2. An anode at the Swedish end of the link made of forty 20 m² “titanium meshes with a special oxide coating of precious metals” [Nyman].

As part of the original construction a trial titanium electrode was also installed by Fingrid: condition assessment some years later showed little deterioration [Ingemansson].

A decade later the link was upgraded to a bipole with the addition of a second pole, namely, Fenno-Skan 2 (800 MW ±500 kV). Conversion to a bipole required the sea electrode system to also be bidirectional, hence the original copper cathode was replaced with a number of shallowly buried meshed titanium nets. Maximum field gradient and step potential design parameters were set and the new electrode system designed to meet these limits with up to 50% of the nets out of service.

Bipolar operation decreased the electrode current to less than a fifth of the original Fenno-Skan 1 monopole design [Fingrid]. Consequently both corrosion and chlorine generation were reduced proportionally. Fingrid had previously monitored corrosion and gave a commitment to continue this programme with the new sea electrode and undertake any necessary remedial actions. Similarly, chlorine production at the anode was reduced and according to Fingrid, “The amount of chlorine is so small that when mixed with sea water, it has no significance. Similar electrodes have been used in the area of the Baltic Sea for 50 years, with no observed impacts on the quality of water or behaviour of fish”.

3.1.1.5 Baltic Cable
The Baltic Cable operating since 1994 comprises a 250 km subsea route between Sweden and Germany and is a ±450 kV 600 MW monopole, although the capacity is restricted due to the German onshore transmission network. The design of the electrode system built on the experience gained from previous projects in the region and underwent a comprehensive planning/testing phase [Tykeson][Nyman].
Alternatives to sea electrodes such as deep hole ground electrodes were also considered. An initial 230 m deep test electrode was successfully demonstrated in 1991 [Nyman] which led to the construction of a 550 m deep ground electrode adjacent to the Swedish converter station which was operated in parallel with the sea electrode. The electrode consists of a titanium mesh coated with precious metal oxides; the same material as the sea electrodes. The current carrying capacity of the ground electrode was rated as a quarter of the full return current.

The choice of sea electrodes was thoroughly reviewed with attention paid to material selection and electrochemical reactions at the electrodes; chlorine and oxygen generation rates at maximum return current (1364 A) were calculated to be 4700 kg/year and 2500 kg/year respectively [Tykeson]. Additionally, theoretical voltage distribution calculations were made for the anode and compared to field measurements of a test electrode installed 500 m from shore: these measurements were the basis for corrosion predictions. The final design consists of an anode with 40 titanium nets each 20 m² laid on the sea bottom under plastic tubes and stones. In contrast the cathode consists of a bare 300 mm² copper conductor ring 1 km in diameter situated in the Baltic Sea north of Elmenhorst [CIGRE 2005].

To investigate the risk of corrosion of nearby metallic objects caused by the return current 3D finite element modelling studies were undertaken. These calculations estimated the stray current flowing in these objects which in turn causes corrosion where the current exits. Factors in the model included the return current, water depth and electrical conductivity of the bottom layers of the seafloor. Based on these analyses in certain cases insulating joints and corrosion protection were applied to cables and pipelines in the area [Faugstad].

### 3.1.1.5.1 Monitoring

In 1993 the Water Right Court in Sweden made it a condition that the cable's and sea electrode's impacts on fisheries and nearby water pipes were monitored; this monitoring was initially planned until 1999 but was later extended to 2001 by the Swedish Environmental Court. Of particular concern was the influence of the magnetic field generated by the link on migrating eels.

In 1999 the National Board of Fisheries concluded that, "nothing has emerged to indicate that the cable prevents the large-scale migration of silver eels out of the Baltic Sea" [Westerberg]. The report also noted that the study "proved the assumption that the eels use a biological compass ..... and that the cable locally can cause a variance in this. The effects of disorientation are so small that inaccuracy in the tracking does not allow a firm conclusion".

Systematic site surveys of benthic flora and fauna were carried out before and after laying the HVDC cable. The results showed that "on the basis 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" [Liljestrand].

A similar methodology was used at the sea electrode location and nearby control sites, once again "no difference in the re-colonization is observed when comparing the test
areas of the electrode station and the reference”. The report however notes that, “the delayed start of operations can in this regard help to mask a possible impact from the electrode station in terms of differences in the re-colonization”.

During the monitoring period more measurements were added to the original test programme. Measurements of pH at the sea electrode site and reference points “correspond to normal values of seawater”. The uptake of organic chlorine (EOCl) was measured using cages of mussels and clams at both the sea electrode and a reference site [Faugstad]. On one occasion elevated EOCl levels were recorded at the reference site, no elevated levels were recorded at the sea electrode site compared to the natural background level. All measurements were “very low compared with levels that cause toxic effects in organisms”.

In October 2002 the Swedish Environmental Court finally closed the probationary period of the Baltic Cable [Ystadsallehanda] concluding:

1. No impact on benthic flora or fauna at the electrode sites or along the cable route.
2. The cable does not have any major impact on the fish but noted that the Fisheries Agency report said, “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”.
3. No corrosive effect from the electrode station on the water pipes in Smygehamn had been proved during the probation period.

The Baltic Marine Environment Protection Commission (Helcom) continues to monitor and report on the impact of man’s activities in the region. In its Initial Holistic Assessment report [Helcom] noise and smothering (from sediment displacement) during cable installation barely register on the Baltic Sea Impact Index (BSII); these factors are ranked, 54 and 55 respectively, out of 62 assessed potential pressures in the Baltic Sea: impacts from operation of the cable systems do not appear on the list.

3.1.1.6 Kontek
Kontek is a 400 kV 600 MW monopole connection between Bjaeverskov on the Danish island of Zealand and Bentwisch in Germany. The subsea cable route is unusual having two submarine sections with a land crossing in between. The project came online in 1995.

The sea return carries 1500 A, with the anode located off Stevns (Denmark); this consists of one hundred 20 m² titanium mesh modules. Each module contains the electrode mesh sandwiched between polypropylene mats. The electrode mesh is coated with several layers of precious metal oxides; this combined with the low current density, 2.5 A/m², favours the development of oxygen rather than chlorine [CIGRE 2005].

The cathode is a bare 400 mm² copper conductor circular loop (approximately 1000 m in diameter) with two connections inside the loop and a total length of 5100 m: this results in a current density of 3.75 A/m² [CIGRE 2005].
To investigate the risk of corrosion of nearby metallic objects caused by the return current 3D finite element modelling studies were undertaken. These calculations estimated the stray current flowing in these objects which in turn causes corrosion where the current exits. Factors in the model included the return current, water depth and electrical conductivity of the bottom layers of the seafloor. Based on these analyses in certain cases insulating joints and corrosion protection were applied to cables and pipelines in the area [Faugstad].

3.1.1.6.1 Monitoring
Similar to the work carried out in Sweden monitoring changes on the seabed in the vicinity of the Baltic Cable anode, a German study by Debus surveyed inside and outside the Kontek ring cathode [Debus 1999]: dredging and bottom grab sampling was performed in 1996 and 1997 to collect epifauna and infauna species. Large variability of the individual densities was observed and no statistical trends were identified. Debus further reviewed the evidence for the effect of electric and magnetic fields on aquatic organisms [Debus 1998]. As with the Baltic Cable there appears to have been concern about migrating fish species. Additionally, no increase in halogenated compounds in sediment or mussels near the anode was discovered [Faugstad].

3.1.1.7 SwePol
The 600 MW 450 kV link between Sweden and Poland runs for 239 km through the Baltic Sea. Originally conceived as a monopolar design with sea return, like many of the other links in the region, local concerns persuaded the owner to add a metallic return path [Abrahamsson]. The principle environmental issue raised during the planning phase was chlorine production at the anode [Andrulewicz]. Of secondary concern was the influence of the magnetic field generated by the monopolar cable on migrating fish species. Exhaustive studies after the installation of both the Baltic Cable and Fenno-Skan links concluded that marine life was not affected by the generated magnetic fields or chemical reactions at the anode [Liljestrand][Westerberg]. Moreover, measurements of hypochlorite at the Baltic Cable anode showed concentrations 100 times lower than that used in the chlorination of drinking water [Söderberg]. During the planning phase of the project a thorough survey was carried out to identify metal objects near the Swedish coast that could be affected by the sea return current. The size and distance of the objects from the electrode were considered and included structures over 5 km in length as far away as 50 km; objects identified included sewage pipes, district heating, medium voltage cables and copper protective shielding. The decision to install the metallic return not only eliminated the generation of chlorine and any potential corrosion issues, it also reduced the magnetic field strength along the cable route.

3.1.1.7.1 Monitoring
Studies by Andrulewicz of macrozoobenthos before and after cable laying [Andrulewicz 2001 cited in Söderberg][Andrulewicz 2003] concluded that, “one year after construction there were no obvious changes in macrozoobenthos species composition, abundance or biomass which could be related to bottom disturbance caused by cable construction. In study area 4, which is the deepest station with a significantly less dynamic bottom than those of other study areas, some indications that the construction
phase could have had an impact were noted in that the mean size of individuals was smaller one year after cable installation”.

3.1.1.8 NorNed
As discussed above, many links in the Baltic Sea have operated successfully as monopoles with sea returns or bipoles with sea electrodes for emergency operation. During NorNed’s development a sea return was the preferred technical solution due to the very long length, 580 km, of the connection [Faugstad]. The environmental impact assessment considered:

- Electrolysis products and impact on marine life
- Impact on marine life from the electrical fields
- Corrosion impact
- Influence of fish migration from the magnetic fields
- Compass deviation caused by the cable’s magnetic field

As highlighted above, monitoring programmes on the impact of other monopole links in the Baltic Sea have shown no detrimental impacts to benthic flora and fauna in the vicinity of the electrodes, from the evolved chlorine/bromine or electric field, and no accumulation of halogenated compounds in sediments or organisms. Nevertheless, NorNed carried out additional studies on new electrode materials that would selectively produce less chlorine than previous generations of electrode (graphite/coke, titanium, coated titanium) [Faugstad]. Additionally no evidence has been observed that the migration patterns of magneto-sensitive fish, such as eels and Atlantic salmon, has been impacted by the existing HVDC links criss-crossing the Baltic Sea.

During the engineering phase of the project, potential corrosion issues were identified by detailed finite element modelling studies of the sea return current on inshore pipelines off the Netherlands coast. Mitigation measures such as sacrificial anodes connected to offshore pipelines have proven highly successful in the past, however, in this case there were many pipelines to consider. One identified solution was locating the sea electrode 60 km offshore. This would have required a new electrode design, increased the risk of damage to the electrode cable, increased operational costs and added considerable project risk [Faugstad]. 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.

3.1.2 Mediterranean
3.1.2.1 SACOI (Sardinia – Corsica – Italy)
The original SACOI link between Sardinia and Italy went into operation in 1967; initially rated at +200 kV 200 MW the 121 km subsea cable route utilised two monopolar cables with a 1500 A sea return. The anode was installed at Punta Tramontana in Sardinia and the cathode near La Torraccia in Tuscany. In 1987 a third leg was added on Corsica with a 50 MW convertor station at Lucciana, making this the first multi-terminal system in the world; a bidirectional ground electrode was installed. The reconfigured system became known as SACOI 1 [Guarniere]. In 1992 the Tuscan and Sardinian convertors were upgraded to ±200 kV 300 MW and the link renamed SACOI 2.
The SACOI anode is located in a small harbour protected by two artificial breakwaters. To protect people and fish from entering the harbour area, and thus being exposed to the generated chlorine and electric field close to the electrode, the harbour is separated from the open sea by nets and a gate. The original anode comprised of 30 titanium tubes spaced at one metre intervals suspended from a pontoon in the harbour; approximately half the tube was activated with platinum [CIGRE 1987, 2005] [EPRI]. In 1995 these were replaced with LIDA® DSA® activated type electrodes: DSA® anodes are titanium anodes coated with a patented mix of metal oxides containing elements such as iridium, ruthenium, platinum, rhodium and tantalum. The anode array was further modified with the installation of the SAPEI interconnector (see below).

Connected to the Italian mainland the cathode is made of simple bare copper conductors supported off the seafloor by concrete blocks located 3 km from the shore in approximately 28 m of water [CIGRE 1987, 2005].

In Corsica the ground electrode can operate as either an anode or a cathode and consists of a line of 50 ferro-silicon-chrome electrodes, placed at 5 m intervals; it is located near the sea, 9 km from the converter station [CIGRE 2005].

The Basslink Draft Integrated Impact Assessment Statement (DIIAS) [Basslink 2001] claims anecdotal evidence showing no impact on the 28 shark species found in the region.

**3.1.2.2 SAPEI (Sardinia – Peninsula Italy)**

Power transfer between Sardinia and the Italian peninsula was significantly enhanced in the late 2000s with the addition of the 1000 MW SAPEI link. This new ±500 kV bipole came into service in 2010; however, it initially operated as a monopole once installation of the first cable was complete (2009). During the period of monopolar operation the sea return operated at maximum capacity, 2500 A, before returning to 1500 A (the original SACOI sea return current) once the second pole went into service.

Key to the design was any interaction with the SACOI link. The main factors considered for the return path were [Ardito][Cova][Di Mario]:

1. The design and siting of an additional cathode on the Italian Peninsula.
2. Upgrading the existing SACOI 2 anode to avoid the construction of an additional anode.
3. Compatibility analysis of the two links from both environmental and electrical design perspectives.
4. Verification of the design for limited polarity reversals under emergency conditions without requiring capacity reduction on the SACOI 2 link.

**3.1.2.2.1 Anode Upgrade**

To enable the reuse of the Punta Tramontana (Sardinia) electrode site, for both normal and emergency operation conditions, required the existing 1500 A anode to be upgraded to 2500 A. The higher current required the anode design to be reassessed to take into account:

- Chlorine production
In order to comply with Italian law (D.Lgs. 152/99 and D.Lgs. 258/00) and European Directive n.60/2000 the maximum permitted chlorine concentration at the harbour entrance was required to be less than 0.2 mg/l. Detailed mathematical modelling was undertaken to assess alternative anode layouts considering the local meteo-marine parameters throughout the year at the harbour, daily tidal movement and hydrodynamic circulation inside the breakwaters. This model was validated against measured hypochlorite concentrations at the SACOI 2 anode in the 1998. Based on the model a new larger linear anode array comprising of 38 rods was designed using the same LIDA® DSA® active electrodes. The model predicted the chlorine concentration would only exceed the (0.2 mg/l) limit more than 30 m inside the harbour entrance.

Electric field measurements close to the harbour entrance prior to upgrading for the SAPEI link showed the field to be 0.6-0.65 V/m (for a return current of 1000 A). Based on these measurements the predicted field under the worst case scenario (return current 2500 A) was 1.5-1.6 V/m. Conservative calculation assumptions showed a good safety margin with respect to the tolerance limit for a person swimming immediately outside the harbour [Di Mario].

Corrosion issues were addressed based on field measurements of the existing SACOI 2 anode and extrapolating to the higher current rating. This indicated that a current density less than 5 mA/m² would be obtained around 5 km from the anode; this current density had been shown to produce very low levels of iron and lead erosion over a 20 year period. The nearest cable prior to the laying of the SAPEI was 10 km from the anode; the closest SAPEI cable would still be 8 km from the anode.

3.1.2.2.2 New Cathode
A new electrode was required on the Italian peninsula near to Latina on the Tyrrhenian coast. Terna and its contractors used the experience gained from both the SACOI 2 (over 40 years in operation) and GrIta link cathodes to design the new SAPEI cathode. The cathode consists of two bare copper conductors each 300 m in length, in an “antenna bipole” configuration eight kilometres offshore and located on the sea floor in approximately 30 m of water. The cathode is connected to the shore using 20 kV 800 mm² XLPE cable [Rendina]. Each of the two branches is capable of carrying 1000 A, allowing the link to operate at full capacity even if one of the branches is out of service. The electric field at the conductor would generate a potential lower than 2 V across the body of a swimmer touching the conductor and the current flowing in the body would be lower than 4 mA [Di Mario].

Based on the performance of other sea electrodes in the region, corrosion was not predicted to be an issue for metallic objects further than 3 km from the cathode.

3.1.2.2.3 Reverse operation
Part of the design specification was to allow short-term polarity reversals on the link while maintaining full power transfer. Performance studies of the LIDA® DSA® “anode” rods operating as a cathode were undertaken and showed that “no surface alteration
resulted after the test” and “chlorine production is measurable only during anode polarisation as expected” [Di Mario]. Likewise studies of the copper “cathode” cables operating as the anode were performed and indicated the rate of copper consumption was 0.2%/year of the cable diameter for each branch. The performance of both electrodes operating under polarity reversal was therefore deemed adequate.

3.1.2.3 Grita
The sea return design of the 400 kV 500 MW Greece – Italy monopolar interconnector drew heavily on the operational experience, upgrading and field measurements taken on the SACOI 1/2 link. The anode is located at the Greek end of the link off the Corfu strait, while the cathode is in Italy close to Cape Otranto.

The anode comprises of 39 electrodes titanium bars made, covered by noble metal oxides (like the LIDA® DSA® electrodes used in Sardinia); the rods are characterised by very high corrosion resistance and a long expected life. The anode is located in a small isolated lagoon, separated from the coast by a thin strip of land. To improve the exchange of water between sea and lagoon three 1 m concrete pipes have been installed [Giorgi].

The cathode is a bare copper conductor installed offshore in about 30 m of water, slightly raised above the sea bottom in order to allow better current exchange and easier inspection during maintenance.

3.1.2.4 Monita (under construction)
The ±500 kV 1200 MW bipole between Montenegro and Italy, known as the Monita link is due to be commissioned in 2017. The link is being installed with a pair of marine electrodes 8 and 1 km off the Italian and Montenegrin coasts respectively [Marchiori]. The electrode system will utilise a titanium mesh anode and bare copper conductor cathode. Although under normal operating conditions minimal current will flow through the sea, the marine electrodes allow emergency operation in a monopole configuration.

The Detailed Spatial Plan prepared by the Montenegrin Ministry of Sustainable Development and Tourism [MMSDT] set out the requirements under which the project was to be designed and sanctioned:

1. The link will normally operate as a bipole although “under extraordinary situations or during maintenance” can be switched to a monopolar arrangement if electrodes are present.
2. Analysis of the Montenegrin coast showed there are no beaches suitable to site electrodes. Pond electrodes were also discounted early in the development phase since possible locations had challenging terrain and difficult access. An analysis for sea electrode usage was carried out.
3. The marine electrode is expected to be a metal construction at least 100 m offshore and at the depth of approximately 30-35 m with lateral dimensions of the order of 600 × 30 m.
4. The electrode shall be anchored to the bottom, be visibly marked and protected from vessels.
5. The electrode should be designed so that the field intensity near the electrode is below the level which may adversely affect humans. The electric field at the surface should ensure the safety of swimmers and, divers, flora and fauna near electrode, even if in physical contact.

6. The impact of the sea electrode on metal objects within 3 km of the electrode should be considered.

7. The final design should consider the recommendations of experts regarding the influence of the electrode on wildlife and use appropriate mitigations.

3.2 Asia Pacific
The Asia Pacific region includes projects with sea returns in Korea, The Philippines and New Zealand; these are all discussed in the following section. Additionally, the Basslink project in Australia is also reviewed in detail since this was planned with a sea return but ultimately following public consultation was installed with a metallic return.

3.2.1 Haenam – Jeju Korea
There are two HVDC connections between mainland South Korea and Jeju Island (or alternatively called Cheju). The original 96 km link, Haeman – Jeju, was commissioned in 1997 and consists of two ±180 kV monopole cables capable of carrying 300 MW [Haddock cited in Alstom]. The return path is provided by two pond-electrodes each consisting of 20 Duralmin electrodes [CIGRE 2005]. These are located hanging below the low tide mark in a lagoon protected by a rock-filled breakwater. The electrode system has a continuous rating of 834 A.

The new link (±250 kV 400 MW) commissioned in 2014 runs for 101 km under the Myeongnyang Strait between Jindo and Jeju, and uses a metallic return [LS Cable].

3.2.2 Leyte – Luzon Philippines
The Philippines has one HVDC transmission link connecting a geothermal power plant on the island of Leyte and the southern part of the main island of Luzon. The 440 MW 350 kV Leyte – Luzon link went in to service in 1998 and is a monopole containing a 21 km subsea section crossing the San Bernardino Strait [CIGRE 2005][Rudervall].

Shore electrodes located at Albuera (Leyte) and Calabanga (Luzon) were assessed to be the most appropriate solution, offering a low loss return path and minimal environmental impact [Correa]. The electrodes are composed of 40 silicon-iron/coke sub-electrodes [Balloch] each having two units (total of 80 units per site). The sub-electrodes are installed in two parallel rows, at depths varying from 10 to 13 m beneath the beach, over a distance of about 200 m along the shore.

Following completion of the work the beaches were restored to their original condition and are open to the public. The measured voltage gradient on the shore and in the water are far below the specified values of 5 and 1 V/m respectively. A few years after commissioning current imbalances were observed between the sub-electrodes at Albuera which exceeded the expected design parameters [Allaire].

The Basslink Draft Integrated Impact Assessment Statement Summary Report [Basslink 2001] claims anecdotal evidence shows no change in shark or ray numbers in the waters around the electrodes where the electric field is highest.
3.2.3 Inter-Island New Zealand

The New Zealand inter-island link between Benmore-Haywards was originally installed as a bipole in 1965 and has undergone several upgrades, most recently in 2013 [Transpower 2013]. From the outset the link had electrode stations at Te Hikowhenua (shore electrode) and Bog Roy (land electrode). Increases in the inter-island transfer capacity over time have required the electrode system also be upgraded from its original 1200 A design to 2000 A (continuous) or 2400 A (intermittent for a few hours) [Transpower 2009].

In planning the latest refurbishment/upgrade Transpower committed that “the condition and adequacy of the electrode will be reviewed for on-going operation and its impact on the environment” [Transpower 2008a]; Transpower has performed many measurements on the electrode system since its inception (see below). Other return path options were considered by Transpower with the company stating [Transpower 2009] “the return current path can be provided through sea and/or ground or via a dedicated metallic return conductor. The preference is to provide a ground/sea return due to the lower resistance and resulting in lower transmission losses”. Whilst considering the continued use of the existing ground/sea return system, Transpower commented that “buried metal corrosion and DC current penetrating AC networks through transformer neutrals have been identified and resolved in the past” [Transpower 2009].

In the early 1960s when the inter-island link was planned very little information regarding earth return-current operation was available. The original land electrode at Bog Roy was a groundbreaking design had a maximum operating current of 1200 A. Factors considered during the design included [O’Brien]:

- Site geology
- Distance to buried metallic objects
- Soil heating
- Electro-osmosis
- Voltage gradient at the ground surface
- Touch potentials

The final implemented design consisted of a six-armed star arrangement made of 40 mm mild steel rods totalling 2028 m in length. The rods are buried in coke filled (0.26 m²) trenches 1.5 m deep. This design avoids soil heating, electro-osmosis and electrolytic effects. Details of the original electrode design parameters and calculations are given in [Kimbark].

Both electrode stations were extended between 1989 and 1993 to increase significantly their current rating to 2000 A (continuous operation) as part of an uprating of the link to ±350 kV: corresponding to 700 MW monopolar operation at 350 kV DC. Three new HVDC cables were also installed at this time to supplement the ageing original cables prior to their replacement. The electrode system is capable of operating at 2400 A for few hours at a time [Transpower 2009].
Between 1965 and 1992 health and safety policy evolved. The original step potential design parameters avoided causing “hazard” to humans and animals, whereas by the time of the upgrade a new more stringent criterion avoided causing “annoyance”; this was defined as a DC body current less than 5 mA under the maximum operating current (2400 A). This was achieved by modifying the original Bog Roy design to a branched-star configuration, thereby increasing the total length to 4024 m [O’Brien].

In 1965 the same design philosophy was used for the Te Hikowhenua shore electrode; however, it was also necessary to consider the impact of the voltage gradient on fish. The original shore electrode consisted of 25 electrode cells, spaced approximately every 7 m, in a 172 m long array. The initial electrodes were linseed impregnated carbon electrodes; however these slowly eroded and were replaced when necessary with silicon-iron electrodes [CIGRE 1987, 2005][EPRI]. As at the South Island electrode avoiding causing annoyance by step or touch potentials, became the upgrading criterion for the shore electrode. Much greater understanding of the ground conditions had developed between 1965 and late 1980s, consequently more information was available to influence the design. The entire original electrode was replaced with 42 new high silicon-chromium iron electrodes spaced at roughly 20 m intervals to create an 881 m long array along the shore. These were buried in porous concrete cylinders deeper than before ensuring all were below the lowest tide mark. To ensure good sea water penetration of the array the entire length was excavated and the rocky areas removed before backfilling: the trench was also connected to the open sea with piping.

A build-up of magnesium hydroxide has been discovered occasionally on the electrode surfaces. This has the effect to reduce the efficiency of individual cells causing a non-uniform distribution of the current across the array and leading to localised rises in potential gradient (see below). Larger diameter electrodes, which lower the local current density, are expected to reduce the rate of formation [O’Brien]. To mitigate this situation Transpower cleans the accumulation of magnesium hydroxide on electrode surfaces at Te Hikowhenua [Transpower 2008b]. During monopolar operation the electrodes require six monthly cleaning “removal of shingle from the beach, opening of the electrode cell, withdrawal of electrodes, cleaning of deposits on electrodes and return of the beach to the previous condition”. Likewise under monopolar operation, Transpower have stated [Transpower 2008b] that the “Bog Roy electrodes deteriorate 15 times faster than during bipolar operation”, consequently to maintain performance, “it is necessary on a yearly basis to refurbish one out of 6 branches of the Bog Roy ground electrode. This requires the yearly supply and installation of 660 meters of mild steel and 165 tons of coke”.

3.2.3.1 Monitoring
From the outset the impact of the sea/ground current return system has been monitored. The main areas of study have been:

- Corrosion
- Interactions with AC networks
- Interactions with humans, animals and marine life

3.2.3.1.1 Corrosion
In the first year following commissioning the link operated as a monopole. Inspection of water piping and neutral earthing conductors at a farm near Bog Roy (acting as the cathode) showed very minor electrolytic corrosion. Facilities such as Benmore Power Station, over 6.5 km from the electrode site showed no evidence of any electrolytic corrosion [O’Brien].

Some corrosion issues of farm fence wire near to the Te Hikowhenua electrode site were observed shortly after the fence was erected in the mid-70s [EPRI]. The posts and battens had been treated with metallic salt preservatives and the fence wires corroded at the staple positions [O’Brien]. Inserting small insulators in the wires solved the problem.

3.2.3.1.2 Interactions with AC networks
Until the link was upgraded in 1992 no influence of the HVDC interconnection on the AC networks of the North or South Islands had been observed. A number of issues have since been seen and more details are given in [O’Brien]; in brief these were:

1. Second order harmonics were detected during the commissioning of the new pole in 1992. This was traced back to 4% of the earth return current entering the convertor transformer via the earthed star point causing DC magnetic saturation.
2. The tripping of a power station 10 km from Benmore on differential protection led to the discovery of DC return current entering the Benmore transformer via the earthed star point and travelling via the connecting overhead line to the local generator transformer.
3. Measurements and analysis of ground potential differences between 13 substations on South Island led to neutral earthing resistors being installed to transformers at a number of sites: two sites required a special earthing resistor arrangement. Similar studies on North Island only identified two sites which required remedial work.
4. Maintenance procedures for overhead lines running north-south from the Benmore region (the overhead lines act as a parallel return path) have needed to be amended due to the risk of DC current arcs being drawn during the removal of temporary earths; this occurs when the link is running as a monopole under high load conditions.

3.2.3.1.3 Interactions with humans
At Bog Roy the original design step voltage was 13.1 V/m, subsequent measurements showed this to be just 4.9 V/m at maximum current (1200 A). Touch potentials up to 75 V were recorded from nearby fences, but these were eliminated by the insertion of insulators into long fence wires. Similar touch potential issues were experienced at Te Hikowhenua and were solved in the same manner. After commissioning step potentials up to 7 V/m were measured, however, by 1989 when some of the electrodes had become silted up causing the highest step potential to rise to 15.5 V/m [O’Brien]. The highest marine potential gradient was 12.1 V/m, corresponding to 4.2 V/m for body immersion. These measurements supported the rebuilding of the shore electrode. Following the work the maximum recorded potential gradient was 5.1 V/m.
O’Brien emphasises that step potential alone is not sufficient to determine if a particular value will cause annoyance [O’Brien]. The local resistivity also needs to be considered to determine the current flowing in the body.

Hydrolysis of seawater leads to chlorine generation in the electrode pits at Te Hikowhenua when the site acts as an anode. Transpower has stated that “service providers working in the pits wear gas monitors and allow time for any chlorine gas to dissipate after opening the lids” [Transpower 2008b].

3.2.3.1.4 Interactions with animals
The Bog Roy site is open to grazing animals, as such a maximum step potential of 13.1 V/m was chosen for the original to ensure the safety of smaller animals (eg. sheep): tests following commissioning recorded actual values of 7 V/m. For the 1992 upgrade the same annoyance criterion used for humans was applied lowering the step potentials for animals. Animals have been grazed at the site without restriction or incident now for over 40 years [O’Brien]. No animals occupy the shore at Te Hikowhenua.

It has been reported [O’Brien] that spiders and other insects successfully live inside the electrode cells seemingly unaffected by any gases generated.

3.2.3.1.5 Interactions with marine life
Surveys in the region of the shore electrode and further along the coast in 1989 prior to the link upgrade found no differences in algae or edible shellfish. Likewise fish species found in the area were typical of the coastline in general. Throughout the life of the electrode there have been no reports of fish, sharks or marine mammals, such as whales, being attracted to the electrode site [O’Brien].

According to Transpower’s 2013 Fleet Strategy for HVDC [Transpower 2013] “marine voltage gradients, caused by erosion of land electrodes and material build-up on sea electrodes, can potentially affect marine life in the vicinity of the shore electrode station. However, the design of the Te Hikowhenua shore electrode is such that the voltage gradient is very low (less than 7 V/m)”.

Field measurements of the electrical characteristics in the immediate vicinity of Te Hikowhenua have been conducted [Whitehead]. The study also documented the presence of sharks and rays near the submarine cable to determine the potential effects of the cable system on the distribution of these species. The work concluded that the HVDC cable system in the Cook Strait did not disturb the general ecology or behaviour of sharks and rays in the waters surrounding the HVDC cable and electrode.

3.2.4 Basslink Australia
The Basslink cable runs for 290 km across the Bass Strait between Tasmania and Victoria in Australia. During the planning of this 600 MW 400 kV project it was envisaged as a monopolar design with a sea return. The initial Draft Integrated Impact Assessment Statement (DIIAS) was conducted on this basis [Basslink 2001]; the report is very detailed, covering all aspects of the marine (and land) installation/operation.

Throughout the Marine Section the DIIAS cites the evidence for insignificant environmental impact from other HVDC links with sea electrodes, such as those in the
Baltic Sea, Italy, New Zealand and The Philippines: the monitoring studies carried out for these projects are discussed elsewhere in this report. The DIIAS focuses on specific local issues to the Bass Strait; specifically the proposed route and installation sites for the sea electrodes.

Following a period of consultation with stakeholders Basslink was modified to include a metallic return cable, removing the need for sea electrodes. Section 3.2.4.3 below reviews the reason for the design change and briefly reviews the impacts to the project. Firstly though the environmental case for the use of sea electrodes is reviewed.

3.2.4.1 Proposed electrode design

A seabed survey determined the preferred location for the anode (in Tasmania) was on an area of seabed consisting of rock and hard sand. Given the seabed conditions a graphite/coke anode comprising of 60 sub-electrodes installed in a concrete housings laid on the seabed was proposed. These would have been distributed in an area of approximately 800 x 300 m leading to a current density at the sub-electrodes of 4 A/m$^2$. Titanium electrodes were also considered resulting in 50% lower chlorine production through electrolysis; nevertheless the graphite/coke electrodes met the environmental targets for Basslink and provided a more cost effective solution.

The original proposed Basslink cathode off the Victoria coast was planned as a ring electrode. The cathode design was bare 300mm$^2$ copper conductor laid in an one kilometre diameter circle with insulated spokes and buried at a depth of approximately one metre. The current density at the cathode would have been 8 A/m$^2$.

3.2.4.2 DIIAS evidence to support the use of sea electrodes

The following is a summary of the evidence and arguments put forward in the DIIAS to support the original case for sea electrodes.

3.2.4.2.1 Construction phase

The impacts of construction activities for the sea electrodes are very similar to those of the main HVDC cable. Factors that were considered included:

1. Water quality – Disturbance of sand and sediments by wet-jetting, trench cutting or rock cover emplacement, would lead to temporary a reduction in water clarity. This was expected to return to background levels within an hour even for the finer sediments.

2. Marine habitat – The preferred route avoided sensitive habitats. The effect of wet-jetting and trench cutting are both localised activities, typically contained to 0.5 m wide. The anode array would have required 60 electrodes placed over an area of 0.04 ha on hard seabed.

3. Marine flora and macroinvertebrates – Transitory changes in water quality during installation were predicted to have no significant impact on phytoplankton, benthic algae or macroinvertebrates.

4. Fish – Localised noise during installation could have driven fish from the immediate area, only for them to return once the noise ends. A moving exclusion zone would have impacted commercial and recreational fishing close to the installation vessel.
5. Marine mammals – Whales and dolphins were predicted to avoid the installation vessel based on past observed behaviour. There are no seal colonies in the vicinity of the project.

6. Marine cultural heritage – The preferred route contained no known shipwrecks or aircraft. Aboriginal sites and artefacts on the land bridge, which existed between Tasmania and the mainland 10,000 years ago, were not expected to have survived.

3.2.4.2.2 Electric fields

At maximum transfer capacity (1500 A) the voltage at the surface of the sea anode and cathode would have been 14 and -7 V respectively. At this load the electric fields were calculated to be 1.000 V/m at the anode surface dropping to 0.048 V/m one metre away. The corresponding values at the cathode were predicted as 1.995 V/m and 0.019 V/m. These values are approximately the same or lower than for sea electrodes in the Baltic Sea. The DIIAS focuses on specific local issues:

1. Marine flora and macroinvertebrates – Neither are known to be electro-sensitive and therefore no impact was expected.

2. Bony fish – These can be electro-sensitive but usually to higher fields (> 6 V/m); well above the maximum design field for Basslink. Video evidence from Konti-Skan showed various bony-fish species at night at or near the electrode sites.

3. Cartilaginous fish – Sharks and rays are electro-sensitive. Sharks can detect 0.5 μV/m electric fields although are insensitive to uniform or DC electric fields. In general the DIIAS predicted no adverse impact although conceded that within a few metres of the electrodes a large shark may detect a potential difference between its head and tail which could influence behaviour; either repelling or attracting the shark. Anecdotal evidence from the projects around Italy report no impact on the 28 sharks species found in the region. Similarly no change in shark or ray numbers has been reported related to the Leyte-Luzon link.

4. Marine mammals – The maximum generated field at the surface of the subanodes, or seabed in the case of the cathode, is less than 0.2 V/m, “well below the 1.25 V/m limit for sea electrodes accessible to marine mammals” [Basslink 2001]. Consequently no impact on marine mammals was expected.

5. Marine cultural heritage – There are no large metallic structures near either electrode. All local wrecks are wooden and any on-board metallic objects too small to suffer corrosion caused by the stray current. Likewise any military ordnance is too small to be effected.

3.2.4.2.3 Magnetic fields

The cable connections to the sea electrodes would carry the same current as the HVDC monopole cable and generate a magnetic field. However the current would flow in the opposite direction and the magnetic fields would therefore oppose each other; if the cables are locate close together then the fields will largely cancel depending on the separation.

The biggest concern with the generated magnetic field was the influence on migratory magneto-sensitive species. However, migration is likely to be away from the inshore sea
electrode cables. As with electro-sensitive organisms the DIIAS draws on experience from other global projects whilst focussing on specific local issues in the Bass Strait:

1. Marine flora and macroinvertebrates – Both have been observed to readily exist on or near sea electrodes; the latter are not believed to be magneto-sensitive. No impact was predicted.
2. Bony fish – Some migratory species are magneto-sensitive. Based on eel and salmon studies in the Baltic Sea the DIIAS concludes that Pacific eels may experience “a minor deviation when passing over the Basslink cable but with no significant impact on migration”.
3. Cartilaginous fish – Some elasmobranches are believed to use their electro-sensitivity to detect the earth’s magnetic field. The DIIAS predicted “no adverse impacts ... on migratory behaviour”.
4. Marine mammals – The DIIAS addresses the possibility that some whale strandings are related to variations in Earth’s magnetic field and that magnetic fields generated by the HVDC cable and electrode cables could influence behaviour. It states no definitive scientific link has been found between strandings and natural magnetic anomalies. Many of the same whale species routinely cross the New Zealand Inter-Island link, and moreover, harbour porpoises migrate over several HVDC cables in the Baltic without incident. The DIIAS concludes, “on present evidence, oceanic cetaceans migrating through the Bass Strait are unlikely to be affected by the Basslink magnetic fields”.
5. Ships’ magnetic compasses – The principal mitigation proposed for compass deviation caused by the Basslink cable was updating of maritime charts with the cable route and warnings to mariners.

3.2.4.2.4 Electrolysis products
The DIIAS reviews the electrolysis chemistry at the electrodes and subsequent side reactions that occur in the surrounding seawater.

3.2.4.2.4.1 Cathode
Magnesium hydroxide and calcium hydroxide can form at the cathode if water exchange is low and the current density greater than 10 mA/m²; the Basslink cathode was designed to have a maximum current density of 8 mA/m². Given the ring electrode design and the operating parameters, precipitation of both hydroxides was considered unlikely to occur.

3.2.4.2.4.2 Anode
Calculations of expected chlorine generation are reported in the DIIAS that take account of local conditions; salinity, temperature, pH, water exchange and electrode design. Based on this work the predicted emissions were calculated to be:

- Chlorine – from 0.083 to 0.277 mg/m²/s, with an average of 0.179 mg/m²/s
- Brominated chlorine-produced oxidants – from 0.5 to 1.7 g/d, with an average of 1.1 g/d.

The main issues related to these electrolysis products are:

- Water quality deterioration near the sea electrodes
Toxicity of chlorine, chlorine-produced oxidants and halogenated organic compounds

Bioaccumulation of these compounds in the food chain

Implications for marine resource usage e.g. commercial and recreational fishing

3.2.4.2.4.3 Water quality

Australia has no water quality criteria for chlorine in seawater consequently the DIIAS used US Environmental Protection Agency (EPA) limits in its submission; chronic criterion 13.0 µg/l, acute criterion 7.5 µg/l. Furthermore, since free chlorine is rapidly hydrolysed to a variety of chlorine-produced oxidants, the USA EPA chronic limit was halved to “derive an ambient water quality criterion of 3.75 µg/l for chlorine-produced oxidants”. This value was used “as a surrogate for the US EPA water quality criteria for chlorine” [Basslink 2001]. Based on these values the US EPA acute criterion would be exceeded within 3.2 m of the anode at maximum chlorine production; similarly this criterion would be exceeded within 1.8 m and 0.3 m of the anode for the average and minimum chlorine production rates respectively. Correspondingly the US EPA chronic criterion would be exceeded within 1.2 m, 3.6 m and 5.5 m of the anode for the minimum, average and maximum chlorine production rates.

3.2.4.2.4.4 Toxicity and bioaccumulation

The lowest concentration of chlorine-produced oxidants and halogenated organic compounds reported to have negative effects on the most sensitive species of marine flora, invertebrates and fish is 10 µg/l. This level was only predicted to occur within 2 m of each subanode.

1. Marine flora – No significant impact to phytoplankton was expected. Benthic algae are more resilient and some species were predicted to colonise the subanode structures as has been observed in the Baltic Sea.

2. Invertebrates – In general the eggs, larvae and juvenile stages are the most sensitive stages in the life cycle of marine invertebrates. Based on the modelled values, no significant adverse effects were predicted with the “possible exception of some species or life stage within about 2 m of the subanodes”. Mobile macro-invertebrates were predicted to be least effected and potentially populate the subanode structures as reported in the Baltic Sea.

3. Fishes – Based on the modelled values no direct toxicity to benthic or epibenthic fish was expected especially since their residence time near the anode is expected to be low. The potential for bioaccumulation of chlorine-produced oxidants and halogenated organic compounds was considered but discounted due to scarcity of exposure; this assertion was supported by numerous studies measuring chemical concentrations in fish and invertebrates living on or near electrodes in the Baltic Sea.

4. Mammals – No impact was predicted on marine mammals. Captive marine mammals are held in seawater with added chlorine two to three orders of magnitude greater than near the anode. No bioaccumulation of chlorine-produced oxidants or halogenated organic compounds is expected since the food chain is expected to be ostensibly free from these compounds. No impact was also predicted for humans.
3.2.4.2.5 Fisheries
Both commercial and recreational fishing activities do not take place close to the proposed anode site. Moreover based on the predicted impact on fish species neither activity was predicted to be effected.

3.2.4.2.6 Heat generation
Heat generation is predominantly an issue concerning the HVDC cable; nevertheless the cable connection to the sea electrodes will also generate heat. Calculations predicted a rise in the seabed temperature immediately above the electrode cables of a few degrees Celsius. The DIIAS suggests the impact on invertebrates would be increased metabolism, growth and productivity. The sea electrodes are only expected to raise seawater temperatures by 0.5 °C close to the electrode surface.

3.2.4.3 Change to metallic return
Throughout the consultation phase and public inquiry process some objections were raised on aspects of the submarine cable design, however, the strongest objections concerned the use of sea electrodes. The Joint Advisory Panel (JAP) was satisfied that the electric and magnetic fields resulting from the use of a sea return would have no significant effect on marine flora and fauna. There was concern about:

1. The toxicity of by-products generated at the electrodes and the JAP was minded to require the use of titanium mesh electrodes as a mitigation measure. These have higher selectivity for oxygen and hence produce less chlorine than the proposed graphite/coke electrodes.
2. The possibility of stray DC currents causing corrosion to long metallic structures. Concerns which the Basslink developers had been unable to resolve to the satisfaction of other linear asset owners.

During the course of project development a gas pipeline was also installed across the Bass Strait changing the perception of corrosion issues. Basslink’s evidence that any corrosion could be mitigated (based on testimony from experts who had worked on similar projects in the Baltic Sea) was accepted by the JAP. However the JAP decreed that “the owners of long metallic structures in and adjacent to the Bass Strait must agree mitigation measures” [Basslink 2002]: unfortunately agreement between Basslink and the other parties could not be found and a metallic return was the only viable alternative. The metallic return was designed as a 1400 mm$^2$ 20kV cable, bundled together with the 1500 mm$^2$ HVDC cable and a fibre optic cable.

3.2.4.3.1 Impact on environmental assessment
The installation of the bundled HVDC cable and metallic return had a number of impacts to the analysis documented in the original environmental assessment [Basslink 2002].

1. Construction phase – No significant change since the bundled cable was installed in the same manner as original individual HVDC cable. Close to shore the construction impacts are reduced due to not installing the sea electrodes or cables to the electrodes from the shore.
2. Electric fields – Elimination of the sea electrodes excludes the possibility of an electric field influencing the behaviour of marine life.
3. Magnetic fields – The addition of a bundled metallic return greatly reduces the magnetic field generated by the bundled pair of cables. The magnetic field from the new cable design operating at full load drops to the local earth’s magnetic field within approximately 10 m.

4. Electrolysis products – Elimination of the sea electrodes completely removes the generation of electrolysis products.

5. Fisheries – No significant change compared to the original design with sea electrodes.

6. Heat generation – Placing the metallic return alongside the HVDC cable adds another heat source, doubling the local heat dissipation. This raises the surface temperature of the buried bundle compared to the case for the single HVDC cable operating with a sea return, leading to a greater temperature gradient in the seabed sediments. Nevertheless calculations predicted surface sediment temperatures less than 1 °C different to ambient conditions leading to no significant environmental impact.

3.2.4.3.2 Cost implications

The change from the original Basslink design with sea electrodes to a metallic return had both positive and negative cost implications [Basslink 2002]:

1. Additional cable design studies for a metallic return led to a more cost effective design than when the project costs were originally assessed.

2. These changes significantly reduced cable shipping costs from Europe and lowered the cable laying costs. The number of cable laying campaigns was reduced from five to three.

3. Bundling the HVDC cable and metallic return only required one trench not two as considered in the original cost estimates.

4. The cost of the metallic return in part was offset against the additional cost of corrosion mitigation measures required in the case of sea electrodes.

5. Cost of the sea electrodes and their installation was eliminated.

6. The use of a metallic return increase the joule losses in the system. At full load (600 MW) the losses increase by approximately 10 MW and at half load (300 MW) by approximately 3 MW. This impacts the financial viability of trading on the link.

3.3 North America

3.3.1 Vancouver Island

The first HVDC connection (DC1) to Vancouver Island from the Canadian mainland was commissioned in 1968. Three subsea cables were laid across the Strait of Georgia before crossing Galiano Island and Parker Island on overhead lines before the final submarine section under the Trincomali Channel. DC1 was rated 260 kV 312 MW; two of the three cables operated in monopolar mode (total 1200 A) with the spare cable used as a metallic return. However, the spare cable and sea return were operated in parallel if the load exceeded 600 A [Cherukupalli].

An additional pole, DC2, was commissioned in 1976: this was a ±280 kV 370 MW bipole. Any unbalance current between the DC1 and DC2 poles was carried by the spare DC1
The land electrode on the mainland at Boundary Bay originally only operated as a cathode, but with the addition of DC2 needed to also act as an anode. It is located behind a dyke on the shore ensuring wet ground conditions. Other sites were considered before Boundary Bay was selected but either presented the risk of anchor damage or in one case the location had “profilic wildlife” [EPRI].

The electrode system originally consisted of 46 DURICHOR electrodes (silicon-iron) immersed in 13ft deep pits filled with high carbon content coke breeze. The maximum voltage gradient was calculated to be 0.5 V/m and the current density 45.7 A/m² at the electrode surface and 5.5 A/m² at the active element.

The anode is installed in a man-made lagoon at Sansum Narrows on Vancouver Island and contains 28 graphite electrodes connected in a 4 x 7 array hanging 0.6 m below the water surface. The anode is designed with a maximum current density of 76.4 A/m² and voltage gradient of 2 V/m at the channel-facing wall of the rock-made barrier. Sansum Narrows was chosen after considering eight small bays; the decision was based on factors including availability of rock-fill for the barrier and, remoteness from habitation, major fish runs and spawning grounds [EPRI].

Some early issues were experienced with corrosion of metallic structures including the failure of TV antenna tower anchor rods and, damage to water pipes and sewer mains. In 2005 ASTM A518 G3 High Silicon Cast Iron Anode Sleds were installed in the Trincomali Channel for cable armour corrosion protection. Small amounts of chlorine generated around the electrodes in Boundary Bay destroyed vegetation for 0.2 m around the electrode elements [BC Hydro] [EPRI].

**3.3.2 Labrador Island Link (under construction)**

The Labrador Island Link (LIL) is part of Lower Churchill Project which also includes the Maritime Link (see 3.3.3). The total length of the 900 MW ±350 kV HVDC connection will be 1100 km and will contain a 35 km submarine cable section between Labrador and Newfoundland. The project is due for commissioning in 2017.

Three cables will be installed under the Strait of Belle Isle between Forteau Point (Labrador) and Shoal Cove (Newfoundland); two operating as a bipole and the third as a spare [Nalcor 2012a]. Directional drilling on both sides of the channel will take the cables approximately 2 km offshore before installation directly on the seabed; the cables will be covered with protective rock berms. Horizontal drilling to this point offshore ensures the cables enter the Strait at a depth which eliminates the risk of iceberg damage. Shoreline electrodes will be constructed at L’Anse au Diable (Labrador) and Dowden’s Point in Conception Bay (Newfoundland).

**3.3.2.1 Preliminary Environmental Assessment**

Prior to the granting of permission for the project a thorough environmental assessment [Sikumiut 2010a, 2010b][Nalcor 2012b] was undertaken using a wide variety of sources including Fisheries and Oceans Canada (DFO), Environment Canada, Newfoundland and
Labrador Departments of Fisheries, together with information from many institutions. A review of the Strait of Belle Isle physical environment was conducted. This included:

- Climate and weather
- Physical aspects (bathymetry, currents, tides, waves, ice conditions)
- Chemical aspects (salinity, temperature)
- Oceanography
- Surficial geology and substrates
- Coastal environments and habitats

The biological environment along the proposed cable route and near the electrode sites was reviewed in detail. The categories considered were:

- Algae
- Plankton – phytoplankton, zooplankton, eggs and larvae of macro invertebrates, and ichthyoplankton
- Benthic invertebrates
- Demersal fish
- Pelagic fish
- Invertebrates – both those of commercial value or interest (shellfish) and non-commercial
- Turtles
- Mammals – whales and seals
- Seabirds

Special attention was given to species listed under the Species At Risk Act (SARA), or those assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Data were collected through a combination of drop video recording, diver mediated video recording and grab samples [Sikumiut 2010a, 2010b][Nalcor 2012b].

3.3.2 Shoreline Electrodes Design

Two shoreline electrodes will be installed to carry the small amounts of current due to voltage imbalances between the bipole cables: this is expected to be less than 1% of the transfer current. Additionally the electrode system may be used to carry the full current under emergency conditions: this is expected to occur for less than 40 hours per year.

The L’Anse au Diable shoreline electrode is enclosed in a natural cove and retained behind a 200 m long 15 m high permeable berm (breakwater) which extends slightly into the Strait. The berm is designed to cope with harsh local weather conditions including pack ice and freezing of the pond. The electrodes will be installed at a depth to ensure continuous immersion throughout the year and allow for tidal variations. The electrode will comprise of between 40 and 60 silicon cast iron electrode elements, spaced at approximately 2 m intervals across the central 100 m of the berm; these will be installed vertically on the berm wall [Nalcor 2012a]. Each electrode element will be enclosed in a PVC pipe and connected to a distribution cable via a junction box on top of the berm.
The Dowden’s Point shoreline electrode will be very similar in design to the Labrador electrode, with the same number of electrode elements installed in the same manner on the berm wall. Two alternatives designs were considered:

1. A pond protruding into Conception Bay enclosing by a 385 m berm,
2. An inshore pond created by excavating a 40-50 m inland channel from Conception Bay and backfilling part of the channel to create a berm separating the pond from the sea.

3.3.2.2.1 Shoreline Electrodes Design Parameters
The following briefly reviews the design characteristics of the electrode system which were used for the environmental impact assessment.

3.3.2.2.1.1 Electric field
The electric field around the electrodes at full load was calculated to be 16.7 V/m at the electrode elements, 9.6 V/m on the berm and less than 1.25 V/m in the sea outside the berm [Nalcor 2012a]. The safe limits are quoted as 95 V/m and 1.25 V/m on the berm and outside the berm respectively [CIGRE 1998].

3.3.2.2.1.2 Magnetic field
The magnetic field generated by the current flowing between the electrodes was assessed for two potential impacts, namely, magnetic compass deviation and marine life. During monopolar operation and maximum load magnetic compass deviation was calculated to exceed 0.5° up to 500 m from both electrodes [Nalcor 2012a]. Under normal bipolar operation the compass deviation was estimated to exceed 0.1° up to 100 m from the electrodes.

The incremental magnetic field at the sea surface caused by the maximum electrode current (under monopolar operation) was estimated to be less than 0.8 μT and 2.2 μT at a distance of 500 m from the L’Anse au Diable and Dowden’s Point electrode sites respectively [Nalcor 2012a]. Under normal bipolar conditions the estimated incremental increase 50 m from the electrodes is less than 0.2 μT and 0.3 μT respectively.

3.3.2.2.1.3 Electrolysis products
All the calculations in the Environmental Impact Statement (EIS) are conservative and assume the worst case for chlorine selectivity (30%) and no gas exchange with the air or through the berm into the sea. Tidal flushing alone through the berm is expected to reduce the values by approximately 50%. For the L’Anse au Diable electrode operating as an anode the maximum chlorine produced per day was estimated as $6.89 \times 10^{-4} \text{g/l}$; under bipolar operation this falls to $4.59 \times 10^{-6} \text{g/l}$. For the Dowden’s Point electrode operating as an anode the maximum chlorine produced per day was estimated as $7.44 \times 10^{-3} \text{g/l}$; under bipolar operation this falls to $4.96 \times 10^{-5} \text{g/l}$ [Nalcor 2012a].
3.3.2.1.4 Water Quality
Sea water parameters and quality were studied along the proposed cable route and around the shoreline electrode sites; water temperature, turbidity and salinity were measured and compared with previous studies [Nalcor 2012b]. In the area close to both electrodes sea water was analysed for:

1. Nutrients (including nitrate, nitrite, nitrogen, phosphorous and orthophosphate)
2. Metals (including chromium, cadmium, mercury, arsenic, boron, selenium and strontium)
3. Petroleum hydrocarbons (including C6 to C32 hydrocarbons, benzene, ethylbenzene, xylene and toluene)

Sediment samples were collected in the area around the L'Anse au Diable electrode site and analysed. The rocky seabed did not allow similar sampling at Dowden's Point.

3.3.2.1.5 Heating
Calculations for the shore ponds predict a maximum temperature rise of less than 0.5 °C under continuous maximum load operation [Nalcor 2012a].

3.3.2.3 Environmental Impact Statement Methodology
A number of Valued Environmental Components (VEC) were identified in the EIS, and for each, a number of Key Indicators (KI) were chosen. Concerns specific to the possible project impact on each VEC were systematically reviewed using available data, modelling and measurements. Five environmental effect descriptors were used to assess the residual effects of the project on each VEC.

3.3.2.4 Fish and Fish Habitat Valued Environmental Component
Three KIs were identified for the Marine Fish and Fish Habitat VEC [Nalcor 2012c], each with a number of associated measurable parameters. These were:

- Benthic habitat
- Marine water quality – including noise, EMF, electric field and heat emissions
- Fish – including macro-invertebrates

The EIS addresses each Key Indicator separately in both the construction phase and during operation and maintenance. The following is a consolidated summary of the information and evidence presented.

3.3.2.4.1 Construction phase
Each KI was assessed for potential impacts during the installation of the HVDC cables and shoreline electrode construction. Adverse effects were identified, such as loss of habitat (caused by berm construction), "sub-lethal/lethal physical effects on benthic biota" during rock dumping and increased turbidity (expected to return to normal levels in 1 to 100 hours). Nevertheless these were assessed to be localised, of low to moderate impact and of short duration.

3.3.2.4.2 Operation and maintenance
Assessing the potential operational impacts of the HVDC cable and electrode system the EIS cites scientific studies including those from direct observations on existing HVDC
links [Nalcor 2012b]. The EIS assumes that no invertebrates or fish will enter the electrode ponds. The environmental impacts of repairs are treated and assessed in the same manner as the construction activities.

3.3.2.4.2.1 Electric field
The maximum field gradient outside of the berm is less than 1.25 V/m. The 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 (ZOI) is likely to be small” [Nalcor 2012c]. The EIS reviews the evidence for elasmobranches and teleosts detecting electric fields, and their associated detection limits, it states that “distributional shifts, changes to feeding behaviour and changes to reproductive behaviour could potentially result from the exposure of macro-invertebrates and fishes” to the electric field generated by the electrode system.

3.3.2.4.2.2 Magnetic field
The EIS reviews the variations which occur naturally in the earth’s magnetic field both spatial (strength, inclination, local magnetic anomalies) and temporal (disturbances caused by solar activity). Based on the scientific literature the EIS chooses 200 nT as a conservative threshold that could be detected by some marine fauna. This field strength is predicted to be exceeded within 50 to 100 m of the electrode sites under bipolar operation and 500 m under monopolar operation [Nalcor 2012c]. To give this context the EIS cites that according to the National Oceanic and Atmospheric Administration (NOAA) there are at least 27 geomagnetic events per year in excess of 200 nT.

The 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 ZOI is likely to be small” [Nalcor 2012c]. The EIS reviews the evidence for various fish species (elasmobranches, salmon, eels etc) detecting magnetic fields and associated detection limits, it states that “distributional shifts, changes to feeding behaviour and changes to reproductive behaviour could potentially result from the exposure of macro-invertebrates and fishes” to the magnetic field generated by the electrode system.

3.3.2.4.2.3 Electrolysis products
The EIS briefly reviews the potential electrolysis products and highlights various toxicity studies on marine fauna [Nalcor 2012c]. It states the “lowest concentration of residual chlorine reported to have toxic effects on aquatic invertebrates and fishes is also 0.01 mg/l” and “fish avoidance responses have been reported for residual chlorine concentrations of .... 0.001 mg/l”. Under bipolar operation the conservative calculations predict chlorine concentrations more than two orders of magnitude lower [Nalcor 2012a] than the value considered toxic for marine fish and invertebrates. Consequently the EIS concludes that “while the electrolysis products at the anode (i.e., chlorine and secondary electrolysis products) can be toxic to marine flora, invertebrates and fishes at certain concentrations, they are unlikely to be this concentrated at the L’Anse au Diable and Dowden’s Point electrodes given the predicted modelling results, and the tidal flushing and high water energy at both electrode site locations”. When considering phytoplankton and zooplankton close to the electrodes the EIS states these “could potentially be affected but the ZOI is likely to be small” [Nalcor 2012c].
The EIS considers the accumulation of organo-halogens in the surficial sediment inside and outside the berms. Taking account of the substrate material and its carbon content the EIS considers these less than “optimal” for this to occur.

3.3.2.4.2.4 Heating
Modelling of the heat generated by the electrode system predicted a maximum change in the salt water ponds of less than 0.5 °C [Nalcor 2012a]. The EIS concludes that “the electrodes will be at least 1 m from the bottom sediment, it is likely that any sediment temperature increase as a result of heat dissipation from the submarine cables and electrodes will be negligible” [Nalcor 2012c].

3.3.2.4.3 Summary
Based on all the evidence presented, mitigations through the design of the system, timeframe over which certain effects will occur and the localisation of the effect, the EIS concludes that the cumulative environmental effect for the fish and fish habitat VEC is not significant for any part or timeframe of the project.

3.3.2.5 Marine Mammals and Turtles Valued Environmental Component
Twenty-two species of marine mammals have been reported in the Strait of Belle Isle and Conception Bay, including 17 species of cetaceans and six species of pinnipeds [Nalcor 2012b]. Additionally, two species of turtle have been recorded in the Strait of Belle Isle and Conception Bay. Some species are listed as endangered by SARA or COSEWIC. Four KIs were identified for the Marine Mammals and Turtles VEC [Nalcor 2012c], each with a number of associated measurable parameters. The four Key Indicators assessed were:

- Baleen whales
- Toothed whales
- Pinnipeds
- Sea turtles

The EIS addresses each KI separately in both the construction phase and, during operation and maintenance. The major issues identified and reviewed in the EIS are:

- Noise during the construction phase
- Potential “physical interactions” (i.e. collisions) with installation vessels
- Electromagnetic emissions from the electrode system

Additional interactions were also identified:

1. Airborne noise could affect seal behaviour near shore-based construction.
2. Changes in plankton/fish numbers and/or distribution caused during construction or operation of the project could impact the food chain of the marine mammals.

3.3.2.5.1 Construction phase
Underwater noise from cable laying ships and rock berm construction has the most potential to affect marine mammals and sea turtles. The horizontal directional drilling of the subsea conduits may also affect this VEC. Construction of the rock berms and
dredging activities for the electrode sites will produce underwater sound and potentially affect this VEC.

The EIS reviews the evidence in the scientific literature on the hearing range of various marine mammals and turtles, and observed behaviours in response to boat and/or construction noise both in terms of avoidance and changes in their own vocalisations [Nalcor 2012c]. Sound pressure calculations were undertaken. Based on this information and the lack of vessel traffic during the construction of the shoreline electrode sites (and associated breakwater berms), the EIS predicts the following responses to sound entering the marine environment from construction of the berms:

1. Baleen and toothed whales – If present in the area behavioural effects, if they occur, are expected to be temporary and localised.
2. Seals – Few seals are expected near either site however behavioural effects, if they occur, are expected to be temporary and localised. If seals haul-out near either shoreline electrode site, they may avoid the area during construction.
3. Turtles – If present near the sites and exposed to underwater construction noise behavioural effects are expected to be minimal.
4. In all cases it is predicted that the potential for temporary or permanent hearing loss caused by the marine or onshore construction activities is negligible.

3.3.2.5.2 Operation and maintenance
Assessing the potential operational impacts of the HVDC cable and electrode system the EIS cites scientific studies including those from direct observations on existing HVDC links [Nalcor 2012b].

3.3.2.5.2.1 Magnetic field
The evidence for baleen and toothed whales being able to detect magnetic fields is mixed. Due to the rapid attenuation of the magnetic field, small area affected, limited exposure time, likelihood that both baleen and toothed whales use more than one navigation system, and their capacity for avoidance, the EIS predicts no likely change in behaviour. Moreover, baleen or toothed whales are unlikely to come near the shoreline electrode sites [Nalcor 2012c].

There is no evidence to show that pinnipeds can detect magnetic fields; hence the field generated by the electrodes will have no influence on behaviour. In contrast, some studies have concluded that some juvenile turtle species use magnetic navigation, but this is not thought to be the case for adult turtles [Nalcor 2012c]. In general few turtles are expected close to the project, although some leatherback turtles may occur near Dowden’s Point. Due to the rapid attenuation of the magnetic field, small area affected, limited exposure time, likelihood that turtles use more than one navigation system, and their capacity for avoidance, the EIS predicts no likely change in behaviour.

3.3.2.5.3 Summary
Based on all the evidence presented, mitigations introduced through the design of the system, time frame over which certain effects will occur and the localisation of the effect, the EIS concludes that the cumulative environmental effect on the marine mammals and turtles VEC is not significant for any part or timeframe of the project.
3.3.2.6 Seabirds Valued Environmental Component

During the planning and consultation phases no major issues regarding effects on seabirds were highlighted [Nalcor 2012c]. However, the EIS considers:

- Anthropogenic noise
- Presence of vessels, vehicles and people
- Artificial lighting
- Operation of the shoreline electrodes

The following key indicators chosen were:

- Migrating shorebirds
- Nesting seabirds (especially colonially-nesting species)
- At-sea (away from nest) seabirds

3.3.2.6.1 Construction

The EIS reviews the likely noise sources which will operate during preparation of the cable landing areas, horizontal drilling activities and building of the shoreline electrode sites; it further models the noise levels at various distances from these activities. The EIS also reviews the probable responses of birds based on the scientific literature and auditory ability of different species.

3.3.2.6.1.1 Shore birds

Construction of the electrode site and berms may disturb shorebirds resting and foraging in the intertidal zone and coastal heathlands, as well as pelagic and coastal waterbirds foraging inshore. Migrating shorebirds may be affected by construction noise leading to changes in feeding or roosting behaviour; at worst the birds may avoid the area and move to similar nearby sites. Both electrode sites present poor habitat for shorebirds comprising bedrock and sand at L’Anse au Diable, and boulder/cobble at Dowden’s point. Any displaced birds can relocate to similar habitat in nearby coves, thus the overall impact is expected to be minimal [Nalcor 2012c].

3.3.2.6.1.2 Nesting birds

The EIS identifies that electrode site preparation and installation activities may affect nesting seabirds particularly if feeding on spawning fish near either site: anecdotal evidence reported that capelin spawn near L’Anse au Diable [Nalcor 2012b]. Mitigation measures recommended included regular maintenance of noise control devices such as engine mufflers.

3.3.2.6.2 Operation and maintenance

Seabirds will likely land in the seawater ponds behind the berms and thus be exposed to the voltage gradient generated by the electrodes. The EIS states the “voltage itself does not cause the effect, but rather the difference in voltage which allows the flow of electricity between two points. Therefore, if a bird lands on the electrode saltwater pond, it can sit there safely” [Nalcor 2012c]. The EIS also highlights the lack of available literature on electric field sensitivity in marine birds. The 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.

### 3.3.2.7 Onshore infrastructure and corrosion

In addition to the assessment of the electrode system on the marine habitat discussed above, the impact of stray DC currents from the electrodes on local power grids and telecom networks, and onshore structures near the pond sites was examined.

Due to its remote location there is little onshore infrastructure in the vicinity of the L’Anse au Diable electrode site. Ground potential rise calculations predict the voltage difference across structures of approximately 100 m, like the nearby service marina, would be negligible; moreover, if the structure were connected to a remote earth (through the power network) there was no risk of significant corrosion [Nalcor 2011]. The stray DC current induced in the local distribution network is calculated to be slightly greater than the threshold to cause electrolytic corrosion in a limited number of distribution pole earth rods: mitigation measures include inspection and replacement of the effected poles. However the stray DC current is below the threshold to cause interference with distribution transformers on the network. Likewise, telephone lines and facilities in the vicinity are predicted to be unaffected since the telephone circuits are insulated.

There is more onshore infrastructure close to the Dowden’s Point electrode site including generation, transmission and distribution networks, industrial facilities and marine infrastructure. Studies of the transmission system predict that the stray DC currents passing through grounded transformer neutrals will be below interference limits and consequently not of concern. Similarly there are expected to be no corrosion issues associated with overhead tower foundations or guy-lines which could impact on their performance. Similar to the region near the L’Anse au Diable electrode site the potential difference across structures, such as bridges and fuel stores, is predicted to be negligible leading to no corrosion concerns [Nalcor 2011].

### 3.3.2.8 Monitoring and Follow Up

No monitoring programme was proposed for specific marine fish, marine mammals, turtles, or seabirds of special conservation concern. However, a programme focussed on the marine habitat will be established and agreed with the Canadian Department of Fisheries and Oceans [Nalcor 2012c]. This will:

1. Monitor any compensation works as a result of “harmful alteration, disruption or destruction” of the marine fish habitat, potentially including the underwater rock berms.
2. Study the actual electric and magnetic field generated by the HVDC cables and electrode system.
3. Study the actual level of electrolysis products generated in the seawater, surficial sediment and biota at varying distances from the electrodes.

### 3.3.3 Maritime Link (under construction)

The Maritime Link (ML) is integrally connected with the LIL project (see 3.3.2). The total length of the 500 MW ±200 kV HVDC connection will be 520 km and will contain a
170 km submarine cable section between Cape Ray (Newfoundland) and Point Aconi (Nova Scotia): two cables will be laid across the Cabot Strait [Emera 2013a].

As with the LIL project, horizontal directional drilling will be used at the cable shore landings. Similar reasons for choosing this technique to the LIL project are cited; pack ice, commercial fishing, subsea bathymetry and protection of sensitive shoreline habitat. At Point Aconi the borehole will exit the seabed in approximately 22 m of water 450 m offshore. At Cape Ray it will be 1 km from shore and a depth of 12 m [Emera 2013a].

3.3.3.1 Preliminary environmental assessment

A preliminary assessment of the marine environment along the cable route and near the shoreline electrode sites was prepared based on prior research and studies undertaken specifically to support the ML project [Emera 2013b], this included:

- Marine geophysical surveys
- Met-ocean study
- Icebergs and pack ice study
- Ambient underwater sound surveys
- Benthic surveys (within the Cabot Strait and at the grounding site locations)
- Sediment transport and dispersion surveys

The biological habitat in the Cabot Strait was investigated using a combination of underwater video and photographs at sites with different seafloor-types identified by other surveys. The near shore marine environment at the potential shoreline electrode sites was assessed in St. George’s Bay (Newfoundland) and Cape Breton (Nova Scotia) [Emera 2013b]. The surveys investigated:

- Shoreline and benthic habitats
- Water quality
- Sediment chemistry and composition.

3.3.3.2 Environmental impact

The ML project uses the same environmental impact methodology as the LIL project (Section 3.3.2), although to date the EIS is not in the public domain. In short the method comprises identifying Valued Environmental Components (VEC) and Key Indicators (KI), and reviewing the likely impact against effect descriptors (direction, magnitude, geographic extent, duration, frequency, and reversibility) [Emera 2013c].

The VECs identified in the Environmental Assessment Report for the Cabot Strait and coastal regions [Emera 2013d] are:

- Species of Conservation Interest (SOCl)
- Commercial fisheries
- Marine environment (excluding SOCl species)

For all the VECs, as for the LIL project, the potential environmental impact during the construction phase and, operation and maintenance phase are treated separately. The species impacted from each VEC are listed and the construction/operational activities which could impact each identified KI reviewed against the scientific literature [Emera
For each VEC the Environmental Assessment Report determines the residual environmental effects, performs an assessment of the cumulative environmental effects and determines the significance of this result. However, at this time the project design has not been finalised, hence, although the review is detailed, it is still somewhat generic. Nevertheless these analyses will form the basis of the EIS.

3.3.3.3 Shoreline electrodes
The ML will use shoreline electrodes of a very similar design to those of the LIL (see 3.3.2.2.1) comprising rock berms retaining seawater ponds containing the electrode rods. All the design criteria, such as field gradient, are the same between the two projects. Numerous sites were assessed for proximity to the converter stations or existing rights of way, access, extent of natural shore protection, and proximity to buried metallic infrastructure. Additional factors considered included land availability, land protection, Mi’kmaq interests (in Nova Scotia), commercial fishery interests, as well as potential interaction with Species of Conservation Interest (SOCl). Ultimately sites near Big Lorraine and Little Lorraine, Cape Breton, Nova Scotia, and Indian Head and St George’s, Newfoundland were selected [Emera 2013a].

Although designed as a bipole, monopolar operation between 40 to 120 hours per year is expected. In bipole mode the sea return will only carry any imbalance current between the cables (less than 1% of total current, equating to 12.5 A at full load); in contrast, during monopolar operation the sea return will carry the full current (1250 A).

The system has however been designed with a “metallic switch” to minimise monopolar operation [Emera 2013a]; under certain outage conditions, the out of service pole (conductor and cable) can be used as a metallic return instead of using the seawater.

4. Summary
Since the first subsea HVDC cable connection was installed between the Swedish mainland and Gotland in the mid-1950s, almost 50 systems have been installed globally, resulting in 41 operational links at the end of 2015: there are an additional dozen projects due to commission before the end of the decade. Sea electrode systems have been utilised since the first link and are still being installed on new projects today. Around 30% of the operational links use sea returns; there is an approximately even distribution between marine, shore and pond electrode types in use today. The decision which design to implement is primarily driven by the topology of the shoreline and seabed, and user experience from previous projects. Although this paper has considered the design characteristics of HVDC links with sea electrode systems under normal operation, the transient performance under fault conditions also need to be considered during the design phase.

The maximum sea return current has effectively peaked at 1500 A since around 1990 with three exceptions;

1. SACOI-SAPEI – the common anode is designed to carry 2500A, although only sees this duty for a fault on one of the SAPEI cables.
2. New Zealand Inter-Island – this connection has undergone multiple upgrades throughout its long service life and uses electrodes capable of carrying 2000 A.
3. Fenno-Skan – the addition of Fenno-Skan 2 to the existing monopole increased the sea return current to 1700 A in the event of a cable fault.

In general for new connections where there are no interactions with existing links high power transfer is today achieved using higher convertor station voltage rather than higher current. This may reduce the risk of corrosion caused by stray current but could locally increase voltage gradients under steady state conditions.

The decision to install a sea return is usually commercially driven based on the total project cost (cable cost, installation, life time losses etc):

1. The trend towards longer HVDC subsea links favours the use of sea electrode systems by avoiding the installation of costly metallic returns. Conversely the trend towards ever higher power transfer capacity may present challenges to the use of sea electrodes in the future and favour the use of bipoles.
2. Sea electrode systems offer a lower resistance alternative to a metallic return due to the high cross sectional area through which the return current flows. This leads to lower electrical losses in the return path. This can be commercially attractive depending on the energy trading arrangements on the HVDC link.
3. More recently, the cost differential between a sea electrode system and alternatives such as bundling the HVDC cable with the metallic return has reduced although needs to be assessed on a case-by-case basis.
4. Sea electrodes can also form part of a project’s risk management strategy providing operational flexibility for bipoles when one of the cables is out of service. In this situation the return current can be carried by the sea return, maintaining 50% load transfer capability until the HVDC cable is back in service. Similarly a link with a damaged metallic return could still operate if a back-up sea electrode system existed.

Given the above it might be expected that the longer operational HVDC subsea links would use sea electrodes, however only a third of the longest links (three out of nine links over 200 km) use sea electrodes. Nevertheless of the remaining six, NorNed, Basslink and SwePol were originally designed with sea returns until environmental concerns (eg corrosion) caused a design change.

Environmental considerations form an integral part of any HVDC project and many studies have been devoted to the environmental impacts of sea returns:

1. Since the early subsea HVDC cable projects were commissioned environmental awareness has become more acute. Detailed environmental impact assessments are required before a project begins. In some cases environmental monitoring is required before and after the installation of the cable and sea electrode system to validate that no significant impact has been caused.
2. Extensive environmental monitoring studies show no significant impact from the construction phase (sediment disturbance, noise or vessel movements) or operational phase (electric field, magnetic field, electrolysis products or heat generation) of sea return systems whether the electrodes are installed on the seabed, the shoreline or contained in ponds.
3. Design criteria have become more stringent over time with lower limits for step and touch potentials. This is also reflected in a change of design ethos from voltage gradients which “do not cause hazard” to “do not cause annoyance”; in some cases local ground resistivity has been factored into the assessment. Voltage gradients in the sea have also generally decreased.

4. Objections to potential corrosion of nearby metallic infrastructure has been the main obstacle to the installation of sea electrode systems. Although remedial techniques have been demonstrated to work, third party asset owners are not always willing to accept the deployment of sea electrodes.

5. Further work

Sea electrode systems have demonstrated to be a highly effective return current path option for 50 years and a great deal of work has been carried out to prove their effectiveness. Nevertheless given the drive to HVDC links with ever higher transfer capacities this could present a number of future challenges for sea electrode systems.

1. Higher return currents could modify the electrolysis chemistry at the anode leading to higher chlorine production. Better modelling of the water movement near the electrode elements would allow more accurate predictions of chlorine generation and the associated by-products from subsequent chemical reactions.

2. For pond electrodes the exchange of chlorine gas with the atmosphere is often ignored when determining the accumulation of chlorine in the pond. Although a conservative approach it does potentially lead to over-sizing of the electrode system and to unnecessary capital investment.

3. For pond electrodes better models of the water exchange between the pond and adjacent sea would provide a clearer understanding of the build-up of chlorine within the pond. Nevertheless is will be highly specific to the design of the pond, local sea/weather conditions, tides etc

4. Higher return currents may cause more corrosion to third party metallic structures many kilometres from the electrode system. Better modelling of the distribution of the return current throughout the sea and sub-seabed rock layers would assist in identifying third party assets at risk of corrosion. This would require better knowledge of the geology between the electrode sites and in particular the rock conductivities beneath the seabed.

5. In addition to more accurate modelling of the return current path under steady state conditions, better models need to be developed to study transient currents and voltages under fault conditions, and any consequent safely considerations.

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### Appendix A – List of past and present subsea HVDC links

<table>
<thead>
<tr>
<th>Project (Country)</th>
<th>Year of installation</th>
<th>Subsea length (km)</th>
<th>Rating (MW)</th>
<th>Voltage (kV DC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Europe</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gotland 1 (Sweden)</td>
<td>1954 to 1986</td>
<td>96</td>
<td>30</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>Dismantled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gotland 2 &amp; 3 (Sweden)</td>
<td>1983 (G2), 1987 (G3)</td>
<td>92</td>
<td>260</td>
<td>±150</td>
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<tr>
<td>Konti-Skan 1 (Sweden - Denmark)</td>
<td>1965 to 2006. Replaced</td>
<td>87</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Konti-Skan 1 &amp; 2 (Sweden - Denmark)</td>
<td>1988 KS2, KS1 upgraded 2006</td>
<td>88</td>
<td>380 (KS1), 300 (KS2)</td>
<td>±285</td>
</tr>
<tr>
<td>SACOI (Italy – France - Italy)</td>
<td>1967, 1986, 1992</td>
<td>119</td>
<td>300</td>
<td>±200</td>
</tr>
<tr>
<td>Skagerrak 1&amp;2 (Norway - Denmark)</td>
<td>1976, 1977</td>
<td>124</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>Skagerrak 3 (Norway - Denmark)</td>
<td>1993</td>
<td>124</td>
<td>500 (Total 1000)</td>
<td>350</td>
</tr>
<tr>
<td>Skagerrak 4 (Norway - Denmark)</td>
<td>2015</td>
<td>137</td>
<td>700 (Total 1700)</td>
<td>500</td>
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<tr>
<td>Cross Channel (UK - France)</td>
<td>1986</td>
<td>86</td>
<td>2000</td>
<td>±270</td>
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<tr>
<td>Fennoskan 1 (Sweden - Finland)</td>
<td>1989, 2013</td>
<td>200</td>
<td>500</td>
<td>±400</td>
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<tr>
<td>Fennoskan 2 (Sweden - Finland)</td>
<td>2011</td>
<td>200</td>
<td>800 (Total 1300)</td>
<td>±500</td>
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<td>Baltic Cable (Sweden - Germany)</td>
<td>1994</td>
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<td>450</td>
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<td>Kontek (Denmark - Germany)</td>
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<td>Swepol (Sweden - Poland)</td>
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<td>Grita (Greece - Italy)</td>
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<td>163</td>
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<td>Moyle Interconnector (UK)</td>
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<td>Troll A 1 &amp; 2 (Norway)</td>
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<tr>
<td>Estlink 1 (Finland - Estonia)</td>
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<td>±150</td>
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<tr>
<td>Estlink 2 (Finland - Estonia)</td>
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<td>650</td>
<td>450</td>
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<td>Project (Country)</td>
<td>Year of installation</td>
<td>Subsea length (km)</td>
<td>Rating (MW)</td>
<td>Voltage (kV DC)</td>
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<td>Strebaelt HVDC Link (Denmark)</td>
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<td>600</td>
<td>400</td>
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<tr>
<td>NorNed Link (Norway - Netherlands)</td>
<td>2008</td>
<td>580</td>
<td>700</td>
<td>±450</td>
</tr>
<tr>
<td>BorWin 1 (Germany)</td>
<td>2010</td>
<td>125</td>
<td>400</td>
<td>±150</td>
</tr>
<tr>
<td>BritNed Link (UK - Netherlands)</td>
<td>2011</td>
<td>250</td>
<td>1000</td>
<td>450</td>
</tr>
<tr>
<td>SAPEI (Italy)</td>
<td>2011</td>
<td>420</td>
<td>1000</td>
<td>±500</td>
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<tr>
<td>Valhall (Norway)</td>
<td>2011</td>
<td>292</td>
<td>78</td>
<td>150</td>
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<tr>
<td>COMETA (Spain)</td>
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<td>400</td>
<td>±250</td>
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<td>East-West Interconnector (UK - Ireland)</td>
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<td>±200</td>
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<td>SylWin 1 (Germany)</td>
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<td>864</td>
<td>±320</td>
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<tr>
<td>BorWin 2 (Germany)</td>
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<td>125</td>
<td>800</td>
<td>±300</td>
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<tr>
<td>Helwin 1 (Germany)</td>
<td>2015</td>
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<td>±250</td>
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<tr>
<td>Helwin 2 (Germany)</td>
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<td>320</td>
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<td>Dolwin 1 (Germany)</td>
<td>2015</td>
<td>75</td>
<td>800</td>
<td>±320</td>
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<tr>
<td><strong>North America</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Vancouver 1 &amp; 2 (Canada)</td>
<td>1968, 1977</td>
<td>33</td>
<td>682</td>
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<tr>
<td>Cross Sound (USA)</td>
<td>2002</td>
<td>40</td>
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<td>±150</td>
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<td>Neptune RTS (USA)</td>
<td>2007</td>
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<td>660</td>
<td>500</td>
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<td>Trans Bay (USA)</td>
<td>2010</td>
<td>83</td>
<td>400</td>
<td>±200</td>
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<td><strong>Asia</strong></td>
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</tr>
<tr>
<td>Hokkaido - Honshu (Japan)</td>
<td>1993</td>
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<td>600</td>
<td>±250</td>
</tr>
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<td>Leyte - Luzon (Philippines)</td>
<td>1997</td>
<td>21</td>
<td>440</td>
<td>350</td>
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<tr>
<td>Haenam - Cheju (South Korea)</td>
<td>1998</td>
<td>96</td>
<td>300</td>
<td>±180</td>
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<td>Project (Country)</td>
<td>Year of installation</td>
<td>Subsea length (km)</td>
<td>Rating (MW)</td>
<td>Voltage (kV DC)</td>
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<td>----------------------------------------</td>
<td>----------------------</td>
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<td>-----------------</td>
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<td>Kii-channel crossing (Japan)</td>
<td>2000</td>
<td>49</td>
<td>1400</td>
<td>±250</td>
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<tr>
<td>Nan’ao Island multi-terminal (China)</td>
<td>2013</td>
<td>10</td>
<td>200/100/50</td>
<td>±160</td>
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<td>Jindo – Jeju (South Korea)</td>
<td>2014</td>
<td>101</td>
<td>400</td>
<td>±250</td>
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<tr>
<td>Zhoushan City multi-terminal (China)</td>
<td>2014</td>
<td>129</td>
<td>400/300/100/100/100</td>
<td>±200</td>
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<td><strong>Australasia</strong></td>
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<tr>
<td>Inter-Island 1 (New Zealand)</td>
<td>1965-1991</td>
<td>42</td>
<td>600</td>
<td>±250</td>
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<tr>
<td>Inter-Island 2 (New Zealand)</td>
<td>1993 upgrade</td>
<td>42</td>
<td>1240, later 1040</td>
<td>-350</td>
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<tr>
<td>Inter Island 3 (New Zealand)</td>
<td>2013 replacement to Pole 1</td>
<td>40</td>
<td>1000, later 1200</td>
<td>350</td>
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<tr>
<td>Basslink (Australia)</td>
<td>2006</td>
<td>290</td>
<td>600</td>
<td>400</td>
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Appendix B – Past, present and future HVDC links with sea electrode systems

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

* Projects currently in delivery