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APPENDIX E ASSESSMENT OF EMF IMPACTS ON MARINE FAUNA

Sun Cable
Australia-Asia PowerLink

Comment #15 Marine Ecosystems - EMF Sensitive Threatened and/ or Migratory Fauna

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1 Introduction

This assessment provides additional information to support a response to the Northern Territory (NT) Environment Protection Agency (EPA) comment received on the Supplemental Environmental Impact Statement (SEIS) for Sun Cable's Australia-Asia PowerLink related to the Marine Ecosystems factor. Item 15 requires additional information on the potential impacts of electromagnetic fields (EMF) on marine fauna, as presented in Table 1.1.

Table 1.1: Additional information requested by the NT EPA

Comment #	Context	Additional information required
15.	Marine ecosystems - EMF-sensitive threatened and / or migratory marine fauna The Supplement refers to a review of studies of EMF impacts on marine fauna produced by the International Cable Protection Committee (ICPC, 2021) (Section 9.5.3.2), and asserts that the review indicates a lack of evidence for positive or negative effects of cable EMF on the species studied, with studies finding no change in biological assemblages along energised cables. The report was not provided and does not appear to be publicly available.	1. Provide evidence of the outcomes of studies of EMF exposure/impacts on marine fauna. 2. Provide a copy of the International Cable Protection Committee (ICPC, 2021) study on EMF impacts on marine fauna. 3. Demonstrate that EMF in proximity to the subsea cable is not predicted to be above a level which may result in behavioural changes in elasmobranchs (sharks and rays). 4. Provide detail about how the proposed method of installing cables (laid on the seafloor, trenched into the seabed generally to a depth between 0.3 – 1 m or protected with armouring) would mitigate potential EMF impacts on marine fauna, and what post-installation verification is proposed.

Source: NT EPA (2023).

This assessment describes the potential EMF impacts on EMF-sensitive marine fauna likely to be present within the Proposal area. This assessment includes:

- Section 2 - Identification of EMF-sensitive marine fauna that have the potential to be present within the Proposal area.
- Section 3 – Review of existing literature to evaluate the potential EMF impacts on the identified marine fauna.
- Section 4 – Description of the existing magnetic and electric fields in the Proposal area and determination of the predicted Proposal-generated magnetic and electric fields.
- Section 5 - Avoidance and mitigation measures to reduce or avoid potential EMF impacts on EMF sensitive marine fauna.
- Section 6 - Assessment of the potential residual EMF impacts on marine fauna.

EMF is comprised of two components, the magnetic field and electric field, which have differing potential impacts depending on the marine fauna. As such, this assessment discusses the potential impacts from magnetic fields and electric fields on marine fauna separately.

2 Baseline Environment

2.1 Marine EMF-sensitive species likely to be present in the Proposal area

The marine fauna considered within this assessment were identified in the Draft EIS (Appendix T) and Supplemental EIS and informed by a search of significant species according to the Commonwealth's *Environment Protection and Biodiversity Conservation Act (EPBC Act)* and the Northern Territory's *Territory Parks and Wildlife Conservation Act (TPWC Act)*. The likelihood of occurrence of identified marine fauna (known to occur, likely to occur, or may occur) within the Proposal area has been determined by the results of the EPBC Act Protected Matters Search Tool (PMST) for nearshore NT waters within the three nautical mile (3 NM) and offshore Commonwealth Marine waters between the 3 NM limit and the Australian-Indonesian maritime border.

The list of marine fauna present in the Proposal area was then further refined and only marine magnetosensitive and/or electrosensitive species that have the potential to be impacted by EMF are summarised in Table 2.1.

In addition to the above, consideration has also been given to the Indonesian shortfin eel (*Anguilla bicolor)* as it is known to occur within the proposal area and has the potential to be impacted.

Table 2.1: Marine EMF-sensitive species likely or known to be present within the Proposal area

Latin name	Common name	EPBC Act (status)	TPWC Act (status)	Likelihood of Occurrence	Migratory
Cetaceans:					
Megaptera novaeangliae	Humpback Whale	VU	–	SL	Yes
Balaenoptera musculus brevicauda	Pygmy Blue Whale	EN	–	SK	Yes
Orcaella heinsohni	Australian Snubfin Dolphin	–	–	SK	Yes
Tursiops aduncus	Indo-Pacific Bottlenose Dolphin	–	–	SK	Yes
Sousa sahulensis	Australian Humpback Dolphin	–	–	SK	Yes
Stenella longirostris	Long-snouted Spinner Dolphin	–	–	SM	Yes
Stenella attenuata	Spotted Dolphin	–	–	SM	Yes
Balaenoptera edeni	Bryde's Whale	–	–	SL	Yes
Balaenoptera physalus	Fin Whale	VU	–	SL	Yes
Orcinus orca	Killer Whale	–	–	SM	Yes
Physeter macrocephalus	Sperm Whale	–	–	SM	Yes
Sea turtles:					
Natator depressus	Flatback Turtle	VU	–	SK	Yes
Chelonia mydas	Green Turtle	VU	–	SK	Yes
Eretmochelys imbricata	Hawksbill Turtle	VU	VU	SK	Yes
Dermochelys coriacea	Leatherback Turtle	EN	CR	SL	Yes
Caretta caretta	Loggerhead Turtle	EN	VU	SK	Yes
Lepidochelys olivacea	Olive Ridley Turtle	EN	VU	SK	Yes
Crocodiles:					
Crocodylus porosus	Saltwater Crocodile	–	–	SL	Yes
Sea snakes:					
Aipysurus foliosquama	Leaf-Scaled Sea Snake	CR	–	SK	No
Aipysurus apraefrontalis	Short-nosed Sea Snake	CR	–	SK	No
Bony fishes:					
Anguilla bicolor	Indonesian Shortfin Eel	–	–	SK	Yes
Elasmobranch fishes:					
Rhincodon typus	Whale Shark	VU	–	SK	Yes
Pristis pristis	Largetooth Sawfish	VU	VU	SK	Yes
Pristis zijsron	Green Sawfish	VU	VU	SK	Yes
Pristis clavate	Dwarf Sawfish	VU	VU	SK	Yes
Anoxypristis cuspidata	Narrow Sawfish	–	–	SK	Yes
Isurus oxyrinchus	Shortfin Mako	–	–	SL	Yes
Isurus paucus	Longfin Mako	–	–	SL	Yes
Carcharhinus longimanus	Oceanic Whitetip Shark	–	–	SM	Yes
Glyphis glyphis	Speartooth Shark	CR	VU	SM	No
Glyphis garricki	Northern River Shark	EN	EN	SM	Yes
Carcharodon carcharias	White Shark	VU	–	SM	Yes
Sphyrna lewini	Scalloped Hammerhead	CD	–	SL	Yes
Manta alfredi	Reef Manta Ray	–	–	SL	Yes
Manta birostris	Giant Manta Ray	–	–	SL	Yes

Source: DCCEEW (2023). EPBC Act categories: CR=Critically Endangered; EN=Endangered; VU=Vulnerable; CD= Conservation Dependent. Likelihood of occurrence categories: SK = Species or species habitat is known to occur; SM = Species or species habitat may occur; SL = Species or species habitat is likely to occur.

3 Literature Review

3.1 Background information

The NT EPA (2023) review of the Draft EIS and SEIS report noted that both documents relied heavily on the findings of the ICPC (2021) review report on EMF studies without providing an independent assessment of the outcomes of studies on EMF exposure/impacts to marine fauna. In addition, NT EPA (2023) noted that the ICPC (2021) review paper was not submitted along with the Draft EIS or SEIS.

Under Item 1 of Comment #15, the NT EPA (2023) requested that Sun Cable provide evidence of the outcomes of studies of EMF exposure/impacts on marine fauna. Given the lack of detailed information in the Draft EIS and SEIS, as well as the ICPC (2021) review document (attached as Appendix 1), an updated review of the literature on the observed effects of EMF on marine fauna present within the Proposal area was undertaken in support of the present assessment.

The objective of the updated literature review is to better understand the potential impacts associated with the Proposal and to assist NT EPA in understanding potential changes to marine fauna behaviour potentially arising from the Proposal's predicted EMFs.

3.2 Literature reviewed

A review of the following was completed:

- The scientific papers that informed the ICPC (2021) report on EMF effects on marine fauna
- Recent (2016-2023) scientific papers

3.2.1 Review of ICPC (2021) documents on EMF effects on marine fauna

An initial review of the ICPC (2021) document was undertaken to confirm the veracity of the conclusion that there was "*a lack of evidence for positive or negative effects of cable EMF on the species studied, with studies finding no change in biological assemblages along energised cables.*"

The scientific papers that informed the ICPC (2021) in its review of EMF effects on marine organisms have been reviewed and a summary of findings is provided in Table 3.1. This review focused on:

- The EMF source.
- The key focus and aims of each study.
- Key findings of each study in relation to potential EMF impacts on marine fauna.
- Identified information and data gaps.

Table 3.1: Independent review of scientific papers and publications reviewed by the ICPC (2021)

No.	Reference	EMF sources	Key focus and aims of the study	Key findings in relation to potential EMF impacts on marine fauna	Identified information and data gaps
Major reviews:					
1	Normandeau Associates et al. (2011)	Offshore windfarm inter-array and export cables. Subsea HVDC power transmission cables.	The Normandeau Associates et al. (2011) was an early review paper that focused on the types of subsea power transmission cables and modelled the expected EMFs from representative cables, as well as summarising available information on the magnetosensitivity and electrosensitivity of marine organisms to natural and anthropogenic magnetic and electric fields. This seminal review paper evaluated the level of confidence the existing state of knowledge up to 2011 and identified information and data gaps that future research and studies should address.	EMFs from cables are not sensed directly by marine bony and cartilaginous fishes and the potential for impact is relatively low.	There are very few peer-reviewed publications on the behavioural responses of marine organisms to power cable EMFs, and even fewer that address larger scale marine community effects of EMF. Marine fauna behavioural responses to electric or magnetic fields are known for some species but extrapolation to impacts resulting from exposure to undersea power cables is speculative. The magnitude and characteristics of EMFs from a given cable; the diverse composition of local biological communities and their patterns of habitat; and resource usage are prime examples of project-specific unknowns. Larger scale studies are needed to identify altered movement patterns of marine organisms that encounter activated cable systems. Little research has been done to determine whether most marine invertebrate species have a capability for sensing magnetic or electric fields.
2	Copping et al. (2016)	Marine AC and DC cables associated with offshore Marine Renewable Energy (MRE) devices such as tidal, wave, and wind energy arrays. Actual EMF assessment is presented in Chapter 6: Effects of EMF on Marine Animals from Electrical Cables and MRE Devices (Pages 106-127)	The Copping et al. (2016) review paper focused on assessing EMF effects of MRE devices and associated power cables on marine life and focussed mainly on AC power cables. Note that EMFs emitted by AC power cables are less relevant to the Proposal's HVDC subsea cables, which only generate static DC magnetic fields. In general, only some offshore MRE subsea export cables are DC and tend to operate at lower power capacity (e.g., 80 to 200 MW) and lower voltage ratings (e.g., range 138–230 kV), compared to HVAC subsea cables with higher capacity (e.g., 600 to 1,500 MW) and higher voltage ratings (200 to 525 kV DC).	The review paper concluded that to date *"there has been no evidence to show that EMFs at the levels expected from MRE devices will cause an effect (whether negative or positive) on any species."* Laboratory and field studies have suggested changes in certain animal behaviours due to exposure to EMF signatures. However, no data have been collected that suggest that additional EMFs from MRE in the marine environment will have significant effects on marine animals.	The Copping et al. (2016) paper states that EMF effects on marine mammals are unlikely, but that EMF may affect marine fish, marine turtles, and marine benthic macroinvertebrates. These identified information gaps for marine fish, turtles, and benthic macroinvertebrates contradicts the Copping et al. (2016) review paper's conclusion that *"MRE devices and electrical cables are not known to cause any negative effects on receptor species"*. Based on the limited existing knowledge related to the EMF emitted by devices and the electrical cable systems and limited understanding of sensitive receptor species and their response(s) to the EMF, it is difficult to make a judgment about the outcome

No.	Reference	EMF sources	Key focus and aims of the study	Key findings in relation to potential EMF impacts on marine fauna	Identified information and data gaps
				Behavioural response to EMF from a cable (or multiple cables) is not sufficient to determine any impact unless significant biological consequences result (such as large-scale redistribution or population changes of magnetosensitive receptors). *Marine mammals* – EMF effects are not likely.	of interactions between marine organisms and MRE device-related EMF. *Marine fish* – Potential EMF effect on certain species' behaviour (navigation, avoidance, attraction). *Marine turtles* – EMF may affect turtle behaviour (navigation, attraction, avoidance). *Marine benthic invertebrates* – EMF may alter nearfield benthic communities (e.g., attraction or avoidance). Studies linked to understanding whether electrosensitive species can respond to any source of anthropo-genic EMF are few, so the evidence base is limited, at best. By extension, this means the evidence to apply to subsea cables and MRE devices is also lacking. Specific studies of the cable characteristics and the resultant EMF with respect to species response through time and spatial extent are required. The lack of evidence to date (i.e., 2016) does not rule out the possibility that negative effects could occur in the future to species not yet considered.
3	Albert et al. (2020)	Review paper on effects on marine invertebrates arising from MRE devices and associated subsea cables EMF emissions.	Albert et al. (2020) reviewed the effects on marine invertebrates arising from MRE devices and associated subsea cables EMF emissions.	This Albert et al. (2020) paper notes that EMF studies on marine invertebrates did not report any attraction or repulsion behaviour towards an artificial magnetic field in eight crustacean species, one echinoderm species, and two mollusc species.	Studies are scarce and invertebrate sensitivity to both natural and artificial sources of magnetic and electric fields is poorly documented. To date (i.e., as at 2020), marine invertebrate species (i.e., mollusc, worms, crustaceans and echinoderms) have been poorly studied. Fundamental data about the magnetosensitivity of some marine invertebrate groups are lacking, creating a knowledge void regarding the impact assessment of magnetic field exposure. Notwithstanding, the review paper by Albert et al. (2020) presents quantitative data of EMF effects on marine invertebrates to magnetic fields with several

No.	Reference	EMF sources	Key focus and aims of the study	Key findings in relation to potential EMF impacts on marine fauna	Identified information and data gaps
					citations, which have been used in the updated literature review (see Table 3.2).
Field studies:					
4	Andrulewicz et al. (2003)	Field study of the SwePol Link subsea HVDC cable system in the Baltic Sea between Sweden and Poland, which is a 600 MW and 450 kV cable operating at 1,300 A. This subsea cable system is monopolar (1 HVDC cable with metallic return cable).	The Andrulewicz et al. (2003) is a dated scientific paper that included measurements of the EMF of an HVDC subsea cable between Sweden and Poland named the 'SwePol Link', which is a 600 MW monopole (HVDC cable with metallic return cable). Only the inclination/declination component of the EMF was measured. The assessment of EMF effects on marine fauna was only based on modelling rather than using the EMF measurements of the operating cable using a magnetometer. Modelling was undertaken to assess EMF declination impacts on bony fish (Teleosteii) such as the European eels (*Anguilla 9runcate*) with the aim of assessing passage across the HVDC cable location.	The results of underwater magnetic field measurements show that the resulting values did not exceed calculated values obtained during model simulations. In the few metres distance of the studied cable system, changes of the magnetic field parameters (e.g., inclination and declination) did not exceed the value of natural changes of the same parameters of the geomagnetic field.	The 'functioning' of the SwePol Link in terms of EMF effects on marine fauna was only based on modelling rather than using the EMF measurements of the operating cable using a magnetometer. Andrulewicz et al. (2003) state that, at present (i.e., 2003), there is no answer to the question regarding the absolute indifference of HVDC subsea cables to migrating fish. This confirms the outdated nature of the Andrulewicz et al (2003).
5	Kuhnz et al. (2015)	Field study of the powered subsea telecommunications cable from the Monterey Accelerated Research System (MARS) to a seabed science node at 891 m water depth. Majority of the 51-km long DC power cable (10 kV rating) and optic fibre cable bundle is buried in the seabed to an average depth of 0.94 m (range 0.6 to 1 m). *Methods:* a) Quantitative megafaunal video transects b) BACI (Before-After, Control-Impact) analytical design.	This 2015 field study by Kuhnz et al. (2015) was based on a survey of an energised 10 kV DC powered MARS telecommunications cable, which supplies power to scientific instruments on the seabed at 931 m water depth. Surveys were undertaken in 2007 through 2008, in 2010, and again in 2014 through 2015. A key focus was on cable installation impacts on benthic marine environment, but also assessed cable EMF effects on Little Skates and other elasmobranchs. This field study was repeated in 2020 by Kuhnz et al. (2020).	During the 2015 cable survey when the cable was powered, densities of the electrosensitive Longnose Skate (*Caliraja rhina*) along the 10 kV DC cable did not differ from an area 50 m away and that that "*the abundance of other elasmobranchs in the area appeared similar between the cable and nearby seabed*". Natural spatial and temporal variation in the density and distribution of benthic macrofauna and megafauna appears to be greater than the effects of the MARS cable. During the 2010 cable survey after the cable was energised, skate densities were lower overall and did not differ (p = 0.90) between cable (9.7/100 m^2) and control (6.3/100 m^2) locations. Nor did the density of other	Aggregations of longnose skate (*Caliraja rhina*) were observed at 303 m depth in early 2008 near the unenergized cable. However, far fewer skates were present in this area after the cable was energised in 2010. However, skate aggregations were only observed in one location at around 300 m water depth, for unknown reasons.

No.	Reference	EMF sources	Key focus and aims of the study	Key findings in relation to potential EMF impacts on marine fauna	Identified information and data gaps
				elasmobranchs in the area appear to vary in association with the cable.	
6	Sherwood et al. (2016)	The Basslink cable across bass Strait has been in operation since 2005. This subsea cable is a 600 MW HVDC monopole with a metallic return cable with a 400 kV rating and current of 1,500 A. Magnetometer surveys across the cable were undertaken when the cable was transmitting 375 MW of power. Background geomagnetic field was 61.7 µT.	Sherwood et al. (2016) provided review of the environmental impacts of constructing and operating the Basslink subsea cable to marine fauna in Bass Strait, with a main emphasis on cable installation impacts.	Magnetic field strengths associated with the operating cable were found to be within 0.8% of those predicted using electromagnetic theory with strength dropping rapidly with distance from the cable, which augurs well for the same modelling approach (Notman, 2022) used for the current Proposal. Beyond 20 m the field was indistinguishable from background. The cable's magnetic field variation decreased rapidly at greater distances until it was barely detectable at 15–20 m above the cable.	No EMF information or data gaps were noted. Where the Basslink bundled cable was encased in cast iron half-shell protectors and laid on hard seabed (rocky reef or bedrock), the armoured cable provided a colonisable surface that was rapidly utilised by reef species as new habitat. While Sherwood et al. (2016) stated that the "*magnetic and electric fields generated by the operating cable do not appear to affect this process and within 3.5 years the armoured cable surface was covered with species comparable to the surrounding reef*". However, no EMF data or information on magnetosensitive species presence or absence on the armoured cable surface were presented.

Based on the literature review of scientific papers reviewed by the ICPC (2021) and summarised in Table 3.1, the ICPC (2021) conclusion that EMF impacts on marine life "*indicates a lack of evidence for positive or negative effects of cable EMF on the species studied, with studies finding no change in biological assemblages along energised cables*", is not inconsistent with evidence and conclusions of the individual scientific papers reviewed by the ICPC (2021).

It is noted that of the six scientific papers used by the ICPC (2021) some of the papers were found to be less relevant to the Proposal as they focused on cable installation impacts (e.g., Andrulewicz et al., 2003; Sherwood et al., 2016) rather than EMF impacts. Two papers focussed on EMF effects of lower powered cables than that proposed in the current Proposal (525 kV), such as the 10 kV powered telecommunications cable by Kuhnz et al. (2015) and the 100 to 200 kV export cables from offshore MRE projects by Copping et al. (2016). The remaining two papers by Normandeau Associates et al., (2011) and Albert et al. (2020) were particularly relevant to the current Proposal, although the former is 12 years old.

3.2.2 Review of recent literature on the EMF effects on marine fauna

A review of recent scientific papers with an emphasis on high powered subsea power cables such as offshore windfarm export cables and HVDC subsea cable systems has been completed. The potential and observed effects of both magnetic fields and induced electric fields on marine fauna are summarised in Table 3.2.

Table 3.2: Updated literature review summary of anthropogenic EMF effects on marine megafauna

No.	Marine faunal groups and species	Reference	EMF sources	Key findings in relation to potential impacts of EMF on marine fauna	Veracity of conclusions and identified information and data gaps
Recent general EMF review papers:					
1	Marine fauna in general	Taormina et al. (2021)	Offshore MRE sector subsea intra-array and export power cables and subsea HVDC cables	Taormina et al. (2021) presented a detailed review and perspectives of EMF generated by cables in the MRE sector, which is based on the collaborative project entitled SPECIES (Submarine Power Cables Interactions with Environment and Associated Surveys). The aim of the Taormina et al. (2021) report was to provide a synthesis of the results of the SPECIES project and the perspectives arising from it, including: • A summary of the different effects that can be generated by subsea power cables. • An overview of the selected study sites. • Fact sheets covering several scientific questions, and presenting the methods developed and implemented as well as the main results of the project.	The characteristics of artificial EMF fields and their potential impacts on marine life are still poorly understood today (i.e., at 2021). More *in situ* measurements of the strength of the magnetic fields produced are needed to better understand and assess the potential impact of this disturbance on marine life.
2	Marine fauna in general	OES-Environmental (2019)	Offshore MRE sector subsea power cables	The international collaborative initiative Ocean Energy Systems – Environmental, which aims to understand the environmental impacts of EMF from offshore MRE and recently developed a process for filtering out low risks (Copping et al., 2020s, 2020b). The evidence base for EMF was examined at two OES-Environmental (2019) workshops held in Italy and Australia. With regards to EMF, the OES-Environmental (2019) workshop participants considered that connections to sites with a small number of converters posed a relatively low risk. This conclusion was justified by the fact that the power flowing through these cables is low compared to that of commercial farm export cables or of connection cables (Copping et al., 2020).	OES-Environmental workshop participants noted that the issue of EMF impacts to marine life is *"still new and that it is important to continue studies on the subject, and notably to perform in situ measurements of electromagnetic fields."*
3	Marine fauna in general	Copping et al. (2020a)	Offshore MRE cables	The Copping et al. (2020a) paper details a risk retirement pathway with application to risks of EMF to marine animals. No regulatory thresholds or guidance for allowable emissions of EMF in the marine environment have been found through in-depth literature reviews. Laboratory and field studies have noted that electro- and magneto-sensitive species have shown clear awareness of the presence of EMF, but do not appear to significantly change their behaviour, including several species of crustaceans under laboratory conditions (Woodruff et al., 2013; Taormina, 2019). Several EMF field studies were unable to detect responses on local marine animals [Kavet and Klimley, 2016; Kavet et al., 2016; Love et al., 2016; Wyman et al., 2018; Kilfoyle et al., 2018], or found that responses by electrosensitive elasmobranchs did not change behaviour significantly (Gill et al., 2009).	While there is no accessible database of EMF emissions by specific sizes and types of cables appropriate for MRE development, data collection should be encouraged, as it will assist developers and regulators in rapidly assessing likely EMF outputs and risks. The Copping et al. (2020a) conclusion relates mainly to small MRE devices in the marine environment and may not be applicable to the higher EMFs generated by offshore wind energy

No.	Marine faunal groups and species	Reference	EMF sources	Key findings in relation to potential impacts of EMF on marine fauna	Veracity of conclusions and identified information and data gaps
				Field studies designed to determine whether EMF emissions might cause a barrier effect—preventing animals from reaching their preferred habitats or feeding grounds—found no evidence to support this hypothesis in European eels (Westerberg and Begout-Anras, 2000; Westerberg and Lagenfelt, 2008), in two commercial species of crab in the United States (Love et al. 2017), or in several species of elasmobranchs or American lobster (Hutchison et al., 2018). On reviewing the risk retirement pathway developed by OES-Environmental (2019), the experts and practitioners felt that the evidence base for EMF indicates that the field and laboratory studies of EMF from cables appear to be at levels below which marine animals living in the vicinity are likely to be harmed, allowing this risk also to be retired.	export cables or subsea HVDC power transmission cables.
4	Marine fauna in general	Copping et al. (2020b)	Offshore MRE cables	Present understanding of the interactions between EMFs and marine animals has benefited from laboratory experiments and field studies using surrogate cables, largely with benthic fish and invertebrates (Siegenthaler et al., 2016; Hustichsion, 2018, 2020). However, significant gaps remain in understanding how pelagic species (e.g., sharks, marine mammals, fish) may react to dynamic cables suspended in the water column (Gill and Desender, 2020). The response of marine animals to EMFs depends on the electro- and magneto-sensitivity of the animal, most notably in certain elasmobranch, teleost, and invertebrate species (Snyder et al., 2019). The levels of EMF reported in many field and laboratory studies are much higher than those expected from MRE export cables (Normandeau Associates et al. (2011) and the evidence to date suggests that the levels are unlikely to keep animals away from their preferred habitats or affect migration patterns (Anderson et al., 2017; Wyman et al., 2018]. The Copping et al. (2020b) summary of accumulative knowledge of interactions with MRE devices with marine animals indicated that *"there will be no significant effects on marine animals due to emissions from EMFs from cables"*.	Work remains to be carried out to ensure that EMF data collected to date (i.e., as at 2020) are reproducible and reflect the overall likely effects of the range of MRE devices being developed and installed.
Cetaceans:					
5	Cetaceans	Gales et al. (2012)	Basslink bundled HVDC cable and metallic earth return (MER)	Gales et al. (2012) appears to be the only scientific publication that purports to show interaction of a cetacean with an operating subsea HVDC cable system. Tracking of the eastern movements of tagged Long-finned Pilot Whales (*Globicephala melas*) indicated they stopped and milled around in the vicinity of the operating Basslink subsea HVDC cable. However, this is not correct as the location where they stopped their easterly movements was 7 km short of the Basslink bundled cable	Gales et al (2012) also stated that *"Whereas it is impossible to determine the extent to which the cable itself was related to the observed behaviours, the possibility that the whales were responding directly to the*

No.	Marine faunal groups and species	Reference	EMF sources	Key findings in relation to potential impacts of EMF on marine fauna	Veracity of conclusions and identified information and data gaps
				(HVDC cable + metallic return cable buried to 1 m depth) and the cable's magnetic field reached the background magnetic field (61,6 μT) level at 5 m (midwater depth of 20 m) to the west of the cable's location. Therefore, the tracked whales could not have detected the Basslink cable magnetic field at 7 km distance. Gales et al. (2012) states that "*Clearly, the submarine cable did not represent a physical barrier because the tracked whales swam across it on at least 14 separate occasions during the study period, both singly and in a group, and often twice within 24h. Apart from the initial encounter, there was little evidence of a change in horizontal movement.*" Therefore, the magnetic fields generated by the Basslink subsea HVDC cable were not a barrier to the movements of Long-finned Pilot Whales.	*structure itself or to associated features, is intriguing and considered worthy of discussion*." The possibility that "*the whales were responding directly to the structure itself or to associated features*" is most unlikely given that the Basslink bundled cable is buried to 1 m depth and is therefore not present at the seabed surface.
Sea turtles:					
6	Sea Turtles (Various species)	Bilinksi (2021)	Geomagnetic field and navigation	There may be some potential effects of subsea HVDC cables on sea turtles, which relates mainly to the proximity of a sea turtle to an unburied subsea cable or the seabed immediately overlying a buried subsea cable. Specifically, sea turtle species feeding on the seabed benthos or epibenthos in the vicinity of subsea cables may have a greater potential for exposure than those species foraging elsewhere in the water column (Normandeau Associates et al., 2011; Hutchinson et al. 2018).	Information on EMF impacts from subsea HVDC cable systems to sea turtles is lacking. However, as the magnetosense of sea turtle is surmised to be involved in orientation and navigation in addition to other sensory cues, the point source of the Proposal's subsea HVDC cables are not anticipated to affect long distance navigation in sea turtles.
Crocodiles:					
7	Various species	Fukuda et al. (2019)	Geomagnetic field	It has been suggested that crocodilians develop homing ability with a magnetic map to detect their position and orientation in relation to a target (Rodda, 1984; Combrink, 2014). However, Combrink (2014) suggested that crocodiles may also use other cues, such as landscape, astronomy or scents, possibly in combination. Combrink (2014) documented the homing ability of a relocated 2.7m female crocodile (*Crocodilus niloticus*) that travelled 178.3 km to its capture site over 136 days. Fukuda et al. (2019) tracked the translocation and release of tagged Saltwater Crocodiles (*Crocodylus porosus*) in the Northern Territory. Five large adult male crocodiles (3.03 m to 4.02 m total length) were translocated and released 100 to 320 km from their capture sites, and three additional male crocodiles (3.67 m to 4.23 m total length) were released at their site of capture as controls.	The Fukuda et al. (2019) study found it is difficult to identify which cues the translocated crocodiles relied upon and did not specifically address or investigate magnetic cues.

No.	Marine faunal groups and species	Reference	EMF sources	Key findings in relation to potential impacts of EMF on marine fauna	Veracity of conclusions and identified information and data gaps
				None of the eight crocodiles that were tracked, from either east or west of the Cobourg Peninsula, ventured along the Peninsula itself, despite the apparently strong need of some individuals to return to their capture site.	
8	Various species	Dominguez-Laso (2008)	Bar magnet attached to head of treatment crocodiles and caimans	Dominguez-Laso (2008) attached magnets to the heads of twenty individuals of American Crocodiles (*Crocodylus acutus*), Spectacled Caiman (*Caiman crocodilus*), and Morelet's Crocodiles (*Crocodylus moreletii*) in different sizes ranging from 1.4 to 4 m total length, before being translocated (3–120 km) and released in Mexico. When a magnet was taped to the animals' ears or cranial plate after capture and removed before release, none of them managed to return to the capture location (at least for 4 years). Interestingly, crocodilians that received this magnet treatment moved their head in several directions after release. Despite the high probability of those without magnets returning to capture sites, none of them returned by July 2008 (the earliest release was in September 2004 and latest in December 2007). Those crocodiles without magnets did not move their head in several directions after release; however, they should have been fitted with a non-metallic metal bar of similar same weight in a proper controlled experiment, which could have provided additional information on head movements and direction in crocodiles without magnets attached.	Evidence of magnetosensory perception in crocodiles is weak as there are many other cues that may be used singly or in combination for long distance crocodile movements such as visual, celestial, auditory, olfactory, gustatory (taste) and haptic (sense of touch) cues as suggested by Combrink (2014) and Reber (2020).
9	Various species	Reber (2020)	Geomagnetic field	Reber (2020) reviewed the different modalities of perception in crocodilians including: vision, audition, olfaction, gustation, sense of touch, and the potential for magnetoreception. Crocodilians can home over large distances (Read et al, 2007), but a detailed investigation of a potential magnetic sensitivity has not been conducted to date (i.e., as at 2020). Considering potential magnetoreception, the *lagenar macula* (part of the inner ear) has been hypothesised to allow crocodilians to sense the geomagnetic field for long-distance orientation (Grigg and Kirshner, 2015).	Specific geomagnetic information and data were not available.
Sea snakes:					
10	Various species	Crowe-Riddell et al. (2019a)	Geomagnetic field	Scale organs known as 'sensilla' are small mechanoreceptors that protrude from the surface of epidermal scales of the head and body of sea snakes that are enlarged and substantially more protruding (dome-shaped) compared to their terrestrial counterparts. A dome-shaped scale organ provides increased surface area for stimuli to be received from multiple directions, possibly enhancing mechanoreception in a marine habitat whereby water motion can be detected.	Evidence of magnetosensory perception in sea snakes is weak as there are many other cues that may be used singly or in combination for long distance sea snake movements such as visual, auditory, and olfactory cues, including dermal phototaxis

No.	Marine faunal groups and species	Reference	EMF sources	Key findings in relation to potential impacts of EMF on marine fauna	Veracity of conclusions and identified information and data gaps
				While an electromagnetic sense is plausible (Povel and van der Kooij, 1997; Lillywhite, 2014), the histological sections of sea snake scale organs obtained by Crowe-Riddell (2019) did not show canals or pores that are indicative of passive electroreceptors such as ampullary-type organs (Bennett, 1971). This suggests that the case for magnetoreception in sea snakes is weak and requires more detailed investigations.	found in Aipysurus sea snakes (Crowe-Riddell et al., 2019b).
Fishes:					
11	European Eel (*Anguilla 16runcate*)	Westerberg and Begout-Anras (2000)	Baltic Cable	Westerberg and Begout-Anras (2000) monitored 37 tagged silver eels (*Anguilla 16runcate*) as they crossed over the Baltic Cable (i.e., a 600 MW, 450 kV, 1300 A subsea HVDC cable system). At 60 m above the cable, there was an increment of 5 μT above the background field of 55.5 μT. Only marginal changes of the swimming direction of silver eels were observed during the crossing, which indicated an effect of the cable. However, migrating eels continued their outmigration after passing the cable's location towards the North Sea. Therefore, the magnetic field generated by the cable did not act as a barrier to eel outmigration. Another follow-up study by Westerberg and Lagenfelt (2008) also noted that outmigrating eels in the Baltic Sea crossing over an HVAC cable slowed down but passed over the cable (Westerberg and Lagenfelt, 2008). Therefore, indicating that high power subsea cables do not present a barrier to eel outmigration.	The authors concluded that the present data was insufficient to give more than an indication that a magnetic compass orientation in eels is probable. Westerberg and Begout-Anras (2000) suggested that with a hydrophone array, it should be possible to obtain sufficiently precise tracking data in future studies.
12	Cartilaginous fish Little Skate (*Leucoraja erinacea*)	Hutchison et al. (2020).	Cross Sound Cable (CSC) subsea HVDC cable system (330 MW, 150 kV, 1,175 A) and Neptune Cable (NC) subsea HVDC cable system (660 MW, 500 kV, 1,320 A)	Hutchison et al. (2020) found ecologically significant behavioural responses to the EMF of the Cross Sound Cable in the electro-sensitive Little skate when exposed maximal magnetic fields on the seabed in the treatment enclosure at these power levels were 51.6, 55.3 and 65.3 μT, respectively, which is a maximal positive deviation of 0.3, 4.0 and 14 μT from the background geomagnetic field of 51.3 μT at the CSC test site. There were significant behavioural differences in the total distance travelled by the Little Skates, their speed of movement, proportion of large turns and their height from seabed when compared between the behaviour in the control and treatment enclosures. The most striking response was that skates travelled much further when exposed to the EMF treatment. Conclusion: Hutchison et al (2020) demonstrated that Little Skates were able to move through the EMF emitted from two buried HVDC cables; however, the changes in behavioural movements may infer important ecological consequences for magnetosensitive and electrosensitive-sensitive species.	The behavioural results of the Hutchison et al. (2020) *in situ* field experiments of caged Little Skates at two HVDC cable sites is limited as free-ranging (i.e., not caged) Little Skates may show avoidance behaviour when initially encountering the cable EMF fields, which avoids or reduces exposure and consequently reduces potential ecological effects. In addition, the unexpected presence of strong AC magnetic and AC electric fields at the cables complicates the interpretation of behavioural effects attributable solely to DC magnetic fields and DC induced electric fields for the Proposal.

3.3 Observed effects of EMF on marine fauna in the Proposal area

Magnetosensitive marine fauna perceive or respond to magnetic field changes. Most magnetosensitive marine fauna can theoretically use magnetic cues to establish a direction of movement relative to the magnetic north (compass orientation) or, more complex, to orient on a magnetic map. In the marine environment there is, so far, evidence for a magnetic map sense in turtles, fish, and crustaceans (Mouritsen, 2018).

The following sections summarise the existing literature on the observed effects of EMF on marine fauna that are sensitive to EMF and may occur within the Proposal area.

As most HVDC cable systems and offshore MRE systems are located in the Northern Hemisphere, most research has been undertaken on Northern Hemisphere marine fauna. Where there is a lack of observed effects on marine fauna that may occur within the Proposal area, these species act as surrogates for southern hemisphere species (e.g., migrating eels from both the northern and southern hemisphere are anticipated to have similar orientation and navigation response to the local geomagnetic fields, given that they have a shared evolutionary history).

3.3.1 Observed EMF effects of Cetaceans

There are several cetaceans that are known, likely, or may occur within the Proposal area (see Table 2.1). Cetaceans are thought to possess a magnetic sense that is used for orientation, navigation, and migration (Torres, 2017; Zapetis and Szesciorka, 2018; Nyqvist et al., 2020). There is evidence to suggest that some cetacean species can detect the geomagnetic fields and may use this to orientate themselves or navigate for seasonal migrations (Zapetis and Szesciorka, 2018; Horton et al., 2020; Nyquist et al., 2020; Zellar et al., 2021). For example:

- Fin whales (*Balaenoptera physalus*): Sighting positions of fin whales in the northeastern United States correlated with areas of low geomagnetic magnitude during migration but not with bathymetric parameters, which indicated the use of geomagnetic cues rather than bathymetric features for navigation (Walker et al., 1992).
- Captive bottlenose dolphins (*Tursiops 17runcates*): In dolphinariums, the bottlenose dolphins approached a magnetic object faster than to an identical non-magnetic object, indicating a magnetic sense (Kremers et al., 2014).

Other evidence for a magnetosense in cetaceans includes cetacean strandings at geomagnetic anomalies. It is known from observations of free-ranging cetaceans, that instances of geomagnetic anomalies have resulted in some live cetacean beach strandings (Walker et al., 2002; Zapetis and Szesciorka, 2018). Based on these observations, researchers have suggested that these cetaceans must also be able to utilise geomagnetic cues in normal circumstances such as navigation and sensing (Klinowska, 1985). Consequently, if cetacean migratory routes or seasonal habitat movements occur in the vicinity of operating subsea HVDC cables, they may be at risk of potential impacts from the magnetic fields.

The potential magnetic field effects on Cetacean species present in the Proposal area include:

- Potential interference with orientation or navigation of cetaceans.
- Potential cause of live shore/beach stranding of those cetaceans that follow magnetic minima towards the coast.
- Subsea HVDC cable magnetic fields acting as a barrier to cetacean movement.

The potential Proposal specific impacts on magentosensitive cetaceans are further assessed in Section 6.1.

3.3.2 Observed EMF effects on marine turtles

There are several marine turtles that are known or likely to occur within the Proposal area (see Table 2.1). Marine turtles are known to use multiple cues (both geomagnetic and non-magnetic) for orientation, navigation, and migration (Normandeau et al., 2011). However, there are indications that their geomagnetic sense is critical for primary orientation to approach the general vicinity of a destination such as nesting beaches and foraging, but that fine-tuning is accomplished by using olfactory and visual cues (Tricas and Gill, 2011).

Lohmann (1994) noted that sea turtles appear to rely on an inclination compass that does not distinguish the polarity of field lines (i.e., north versus south); instead, an inclination compass functionally defines 'poleward' as the direction along the Earth's surface in which the angle formed between the total field vector and the gravity vector is smallest (Wiltschko and Wiltschko, 1972).

A literature review did not reveal any threshold levels of geomagnetic sensitivity. However, laboratory studies (e.g., artificial displacement experiments) can be used to infer changes of the magnetic field that may result in a changed orientation of groups of magnetosensitive animals. For example, Fuxjager et al. (2011) observed disorientation of juvenile loggerhead turtles exposed under laboratory experimental conditions to magnetic fields in the range 44.0 to 51.1 µT. The results are consistent with the hypothesis that loggerhead turtles entering the sea for the first time possess a navigational system in which a series of regional magnetic fields sequentially trigger orientation responses that help steer turtles along the migratory route.

Much of what is known about marine animal responses to the geomagnetic field comes from studies of sea turtle migration, and especially loggerhead turtles (*Caretta caretta*). Based on field and laboratory studies, Putman et al., (2015) assessed the magnetic navigation of the oceanic life stages of loggerhead turtles. The conclusion of these studies was that the navigation behaviour of sea turtles was closely tied to the interactions between oceanic circulation and the dynamics in the geomagnetic field.

Identified potential interactions of sea turtles and impacts with magnetic fields associated with the Proposal's subsea HVDC cable system include:

- Effects on navigation/orientation in this species using the geomagnetic field for positioning.
- Effects on migration and other movements, including acting potentially as a barrier.
- Effects on predator/prey interactions.

The potential Proposal specific impacts on magentosensitive marine turtles are further assessed in Section 6.2.

3.3.3 Observed EMF effects on crocodiles

One species of crocodile, the Saltwater Crocodile (*Crocodylus porosus)*, is likely to be present within the Proposal area. Crocodilians can home over large distances (Read et al., 2007), suggesting that crocodilians develop homing ability with a magnetic map to detect their position and orientation in relation to a target (Rodda, 1984; Combrink, 2014). However, evidence of magnetosensory perception in crocodiles is weak as there are many other cues that may be used singly or in combination for long distance crocodile movements such as visual, celestial, auditory, olfactory, gustatory (taste) and haptic (sense of touch) cues (Combrink, 2014; Reber, 2020).

3.3.4 Observed EMF effects on sea snakes

Two species of sea snakes, the Leaf-Scaled Sea Snake (*Aipysurus foliosquama*) and the Short-nosed Sea Snake (*Aipysurus apraefrontalis*), are known to occur within the Proposal area. Sea snakes have scale organs known as 'sensilla' which are small mechanoreceptors that protrude from the surface of epidermal scales of the head and body. However, evidence of magnetosensory perception in sea snakes is weak as there are many other cues that may be used singly or in combination for long distance sea snake movements such as visual, auditory, and olfactory cues, including dermal phototaxis found in Aipysurus sea snakes (Crowe-Riddell et al., 2019b).

3.3.5 Observed EMF effects on bony fishes (Teleosteii)

The Indonesian Shortfin Eel (*Anguilla bicolor*) undertakes migrations to breeding grounds off the east African coast near Madagascar (Bell-Cross and Minshull, 1988) and are likely to pass across the AAPowerLink Subsea Cable System in the Beagle Gulf and Timor Sea. As observed in some magnetosensitive species of bony fishes, the Indonesian Shortfin Eel is understood to use the static (DC) geomagnetic field for orientation, homing, and navigation during migration.

A study of the effects of EMF from HVDC subsea cables on European eels (*Anguilla Anguilla*) identified a minor course deviation of tagged eels was observed when passing over the subsea HVDC Baltic (600 MW, 450 kV, and 1364 A) during outmigration from the Baltic Sea to North Sea (Westerberg and Begout-Anras, 2000). The study noted that the trajectory of the out-migrating eels deviated northwards by about 100 to 220 m as they crossed the subsea HVDC cable's location and suggested that they used an inclination magnetic compass rather than a polar compass for orientation. The initial reason for the Westerberg and Begout-Anras (2000) field study was to test if the Baltic Cable presented a barrier to the out-migrating eels, which was proven not to be the case.

Based on the above, the potential impact of the Proposal on migration of the Indonesian Shortfin Eel is further assessed in Section 6.5.

3.3.6 Observed EMF effects on cartilaginous fishes (Elasmobranchii)

There are several elasmobranchs that are known, likely, or may occur within the Proposal area (see Table 2.1). Elasmobranchs are not known to possess mechanisms or structures (e.g., biomagnetite) that can directly detect magnetic fields, although Anderson et al. (2017) suggested that there were some indications of magnetic field sensing by juvenile sandbar sharks (*Carcharhinus plumbeus*). However, elasmobranchs potentially use their electroreception and electric induction (as they swim through the sea) to sense magnetic fields (Molteno and Kennedy, 2009). A review of Anderson et al. (2017) revealed that the authors could not definitively conclude that the responses observed resulted solely from perception of the magnetic stimulus rather than perception of any electrical fields. Therefore, it has been assumed that magnetic fields are detected indirectly via their electrosensory systems.

The electrosensory system of elasmobranchs comprises electroreceptors (hair cells) located at the end of vase-like structures called 'ampullae of Lorenzini' and a series of nuclei within the brain for processing the electrosensory information arriving from the afferent nerves that innervate the ampullae. Elasmobranchs use their electroreceptors to detect the electromotive force induced by their own movement through seawater and to detect induced electric fields arising from the movement of seawater through the geomagnetic field (Bodznick et al., 2003).

Geomagnetic fields

Elasmobranchs can sense local geomagnetic fields by processing this electrosensory information to separate electric and magnetic information or use both at the same time (Kalmijn, 1999). This indirect sensing of the geomagnetic field may be used for orientation (Mouritsen, 2018), which is highlighted below in the case of scalloped hammerhead sharks.

Large numbers of scalloped hammerhead sharks (*Sphyrna lewini*) converge by day and aggregate over a basaltic seamount in the northern Pacific Ocean (Klimley, 1993). At night, the sharks swim long distances to deep water feeding grounds, where they consume squid and by dawn, they return to the seamount. The question arose as to how they found their way back so reliably. Klimley (1993) followed the sharks on their return journey, while towing a magnetometer behind their research vessel and found that the sharks were following magnetic paths back to the seamount. The seamount was a positive magnetic anomaly (higher than background), and the sharks were assumed to be following the magnetic gradient to retrace their route.

Electric fields

The ampullary electroreceptors of elasmobranchs are insensitive to uniform or constant DC electric fields; that is, an external voltage step will evoke a transient response from a receptor at the step; but within a few seconds, the discharge rate of the primary afferent will return to the pre-step value, thus adapting completely (Neiman et al., 2000). However, the electroreceptors appear to be acutely sensitive to abrupt changes in voltage gradients, especially pulsating sources, such as the AC bioelectric fields emanating from elasmobranch prey species.

The ampullary electroreceptors not only detect electric fields, but also their direction and intensity. The weak, self-generated electric fields created by an elasmobranch's own swimming movement through the geomagnetic field (including HVDC cable magnetic fields), as well as by other movements such as breathing, can activate the electroreceptors. However, electrosensory neurons within an elasmobranch's brain are known to be selectively insensitive to self-generated electric fields while simultaneously retaining their responsiveness to important biological fields, such as electric fields generated by prey movements. Bodznick et al. (2003) carried out electrophysiological and neuroanatomical studies of skates and found that electrosensory neurons within the hindbrain learn to recognise and cancel any stimuli that are consistently associated with an elasmobranch's own movements.

Table 3.3 present a summary of the sensitivity of different elasmobranch species to external electric fields.

Table 3.3: Elasmobranch electroreception sensitivity

Common name	Latin name	Sensitivity		Reference
		(nV/cm)	(μV/m)	
Dusky smooth-hound	*Mustelus canis*	5.0	0.5	Kalmijn (1982)
Mangrove whipray	*Urogymnus granulatus*	4.0	0.4	Haines et al. (2001)
Blacktip reef shark	*Carcharhinus melanopterus*	4.0	0.4	Haines et al. (2001)
Dwarf sawfish	*Pristis clavata*	1.0	0.1	Kalmijn (1966)
Scalloped hammerhead	*Sphyrna lewini*	1.0	0.1	Kajiura and Holland (2002)
Sandbar shark	*Carcharhinus plumbeus*	1.0	0.1	Kajiura and Holland (2002)

Note: Whilst used widely in the scientific literature, the elasmobranch electric sensitivity unit of nV/cm is not a standard SI unit. Therefore, electric field units of μV/m are also given in the table to facilitate the comparison between the weak electric fields (μV/m) induced by seawater flowing through the Proposal's subsea power cable magnetic fields.

In general, EMFs around many subsea power cables fall within the electrosensory detection range of elasmobranchs, and consequently, there is concern that the EMFs may have a behavioural impact on benthic elasmobranch species that encounter them (Orr, 2016; Normandeau Associates et al., 2011). Identified potential interactions and potential EMF (induced electric field component) effects on elasmobranchs include:

- Behavioural effects (e.g., avoidance, attraction, or repulsion).
- Effects on navigation/orientation for those species using the geomagnetic field for positioning.
- Effects on migration and other movements, including acting potentially as a barrier.
- Effect on predator/prey interactions.

The potential Proposal specific impacts on elasmobranchs are further assessed in Section 6.6.

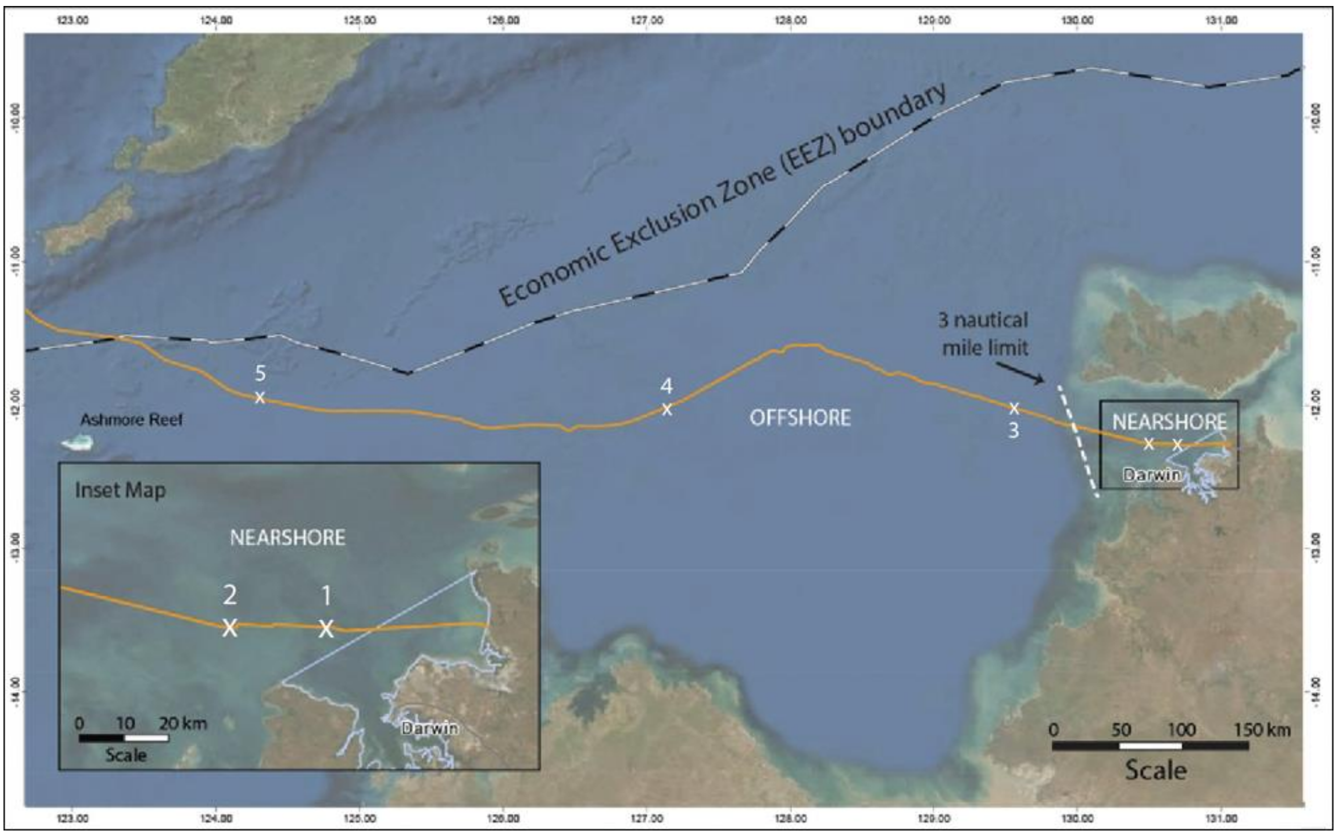
4 Predicted Proposal EMF Fields

4.1 EMF component fields

EMFs are comprised of two components: the magnetic field and the electric field. This section describes:

- The existing background magnetic field
- The existing background electric field
- The predicted proposal magnetic field
- The predicted proposal induced electric field

Notman (2022) modelled background and Proposal generated EMF at six locations within Australian waters. Figure 4.1 shows the Proposal Subsea Cable System in the Beagle Gulf and Timor Sea – these are described in the subsequent sections below.



Note: The sixth location is not shown on this map as it occurs outside of Australian waters.

Figure 4.1: Location map of the Proposal Subsea Cable System

4.2 Existing background magnetic fields

The Earth's natural magnetic field within the Proposal area (i.e., from cable landfall in Shoal Bay (NT) to the Australian-Indonesian maritime border) is described below to enable comparisons with Proposal-generated magnetic fields. For the purposes of this assessment, the Earth's natural magnetic field is referred to as the geomagnetic field.

4.2.1 The geomagnetic field

The geomagnetic field is a combination of several magnetic fields generated by various sources, which are superimposed and interact with each other. More than 90% of the geomagnetic field measured is generated internally as the main field. The remaining 10% arises from the differential flow of ions and electrons inside the planet's magnetosphere and in the ionosphere (NCEI, 2022). These external currents vary on a much shorter time scale than the internal main field, which varies slowly in time and is relatively stable.

The geomagnetic field is a vector quantity that can be considered to have three components an inclination, a declination, and an intensity (or magnitude or strength).

The inclination represents magnetic field lines that emerge from the planet forming an angle to the Earth's surface with latitude, whilst the declination refers to the angle of magnetic field lines with respect to true geographic north, which reflects the direction of a compass needle point.

Since the magnetic fields are vectors, they can be summed. For example, two vectors pointing in the same direction can be summed whilst two vectors pointing in opposite direction can be subtracted from each other.

Descriptions of the local geomagnetic field in nearshore NT Waters and offshore Commonwealth marine waters are provided in a report prepared by Cable Consulting International (CCI) Limited (Notman, 2022), and are summarised below (the Report is also attached as Appendix 2 of this assessment).

Nearshore local geomagnetic fields in the Beagle Gulf

Table 4.1 shows the local geomagnetic fields at two of the study's nearshore EMF calculation marker points within Beagle Bay.

Table 4.1: Nearshore geomagnetic fields at EMF study marker points

Parameter/Component	Marker 1	Marker 2
Latitude	12.27795155° S	12.27299949 S
Longitude	130.75341392 E	130.49877964 E
Total magnetic field	46.1583 µT	46.1729 µT
Horizontal component	35.7454 µT	35.7624 µT
North Component	35.7206 µT	35.7386 µT
East component	1.3306 µT	1.3025 µT
Vertical component	-29.2037 µT	-29.2061 µT
Declination	2.1333°	2.0873°
Inclination	-39.2485°	-39.2375°

Source: Notman (2022); Presented as Appendix 2 of this assessment.

Offshore local geomagnetic fields in the Timor Sea

Table 4.2 shows the local geomagnetic fields at three of the study's offshore EMF calculation marker points (Markers 3, 4 and 5) along the proposed alignment of the AAPowerLink Subsea Cables System within the Timor Sea.

Table 4.2: Offshore geomagnetic fields at EMF study marker points

Parameter/Component	Marker 3	Marker 4	Marker 5
Latitude	11.96621221° S	11.88296104° S	12.04020878° S
Longitude	129.38326808° E	127.39944085° E	124.99650192° E
Total magnetic field	46.0623 µT	46.1378 µT	46.3724 µT
Horizontal component	35.9417 µT	36.0893 µT	36.1576 µT
North Component	35.9228 µT	36.0759 µT	36.1492 µT
East component	1.1668 µT	0.984 µT	0.8248 µT
Vertical component	-28.8085 µT	-28.7446 µT	-29.0337 µT
Declination	1.8603°	1.5625°	1.3070°
Inclination	-38.7134°	-38.5369°	-38.7629°

Source: Notman (2022); Presented as Appendix 2 of this assessment.

The natural background total geomagnetic intensities at each EMF calculation point (i.e., Markers 1 through 5 shown in Figure 4.3) will be compared with the Proposal's HVDC cable-generated magnetic fields in the subsequent sections of this assessment to identify the extent and range of potential impact associated with the proposal.

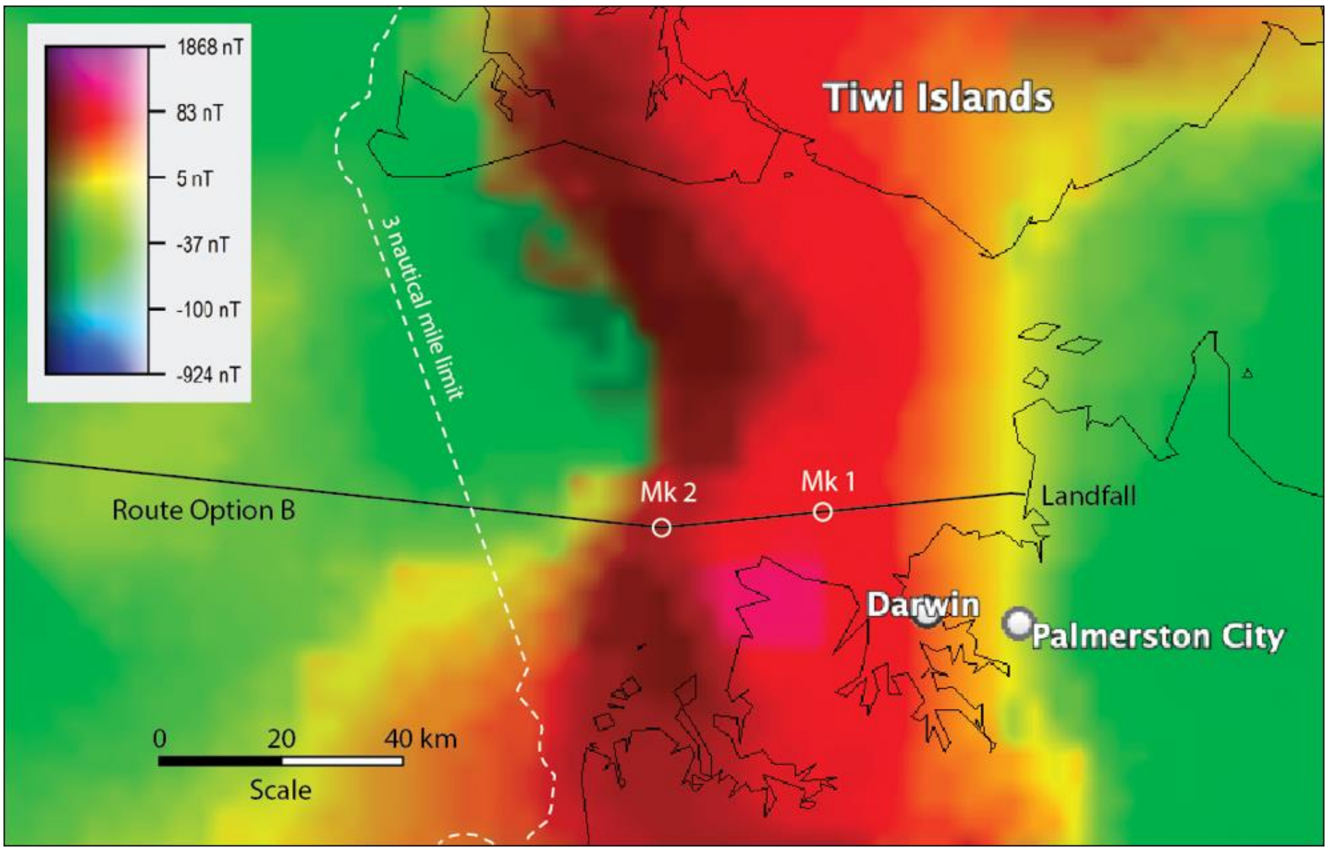
Ionospheric magnetic fields

Another magnetic source in the marine environment is generated by solar wind, which is a stream of energetic particles ejected by the sun. The flux of the particles hits the upper atmosphere and creates ions, which form electric currents in the ionosphere that give rise to magnetic field fluctuations at the Earth's land or sea surface, where the magnetic field has a strength of between 0.001 and 0.01 µT on a solar quiet day. However, after a solar eruption (about every 11 years depending on sunspot activity), the solar wind is stronger and can give rise to magnetic storms where the magnetic fields at the Earth's surface can be several hundred nanoteslas, which is around two orders of magnitude less than the geomagnetic field (Gill et al., 2014).

Natural magnetic anomalies

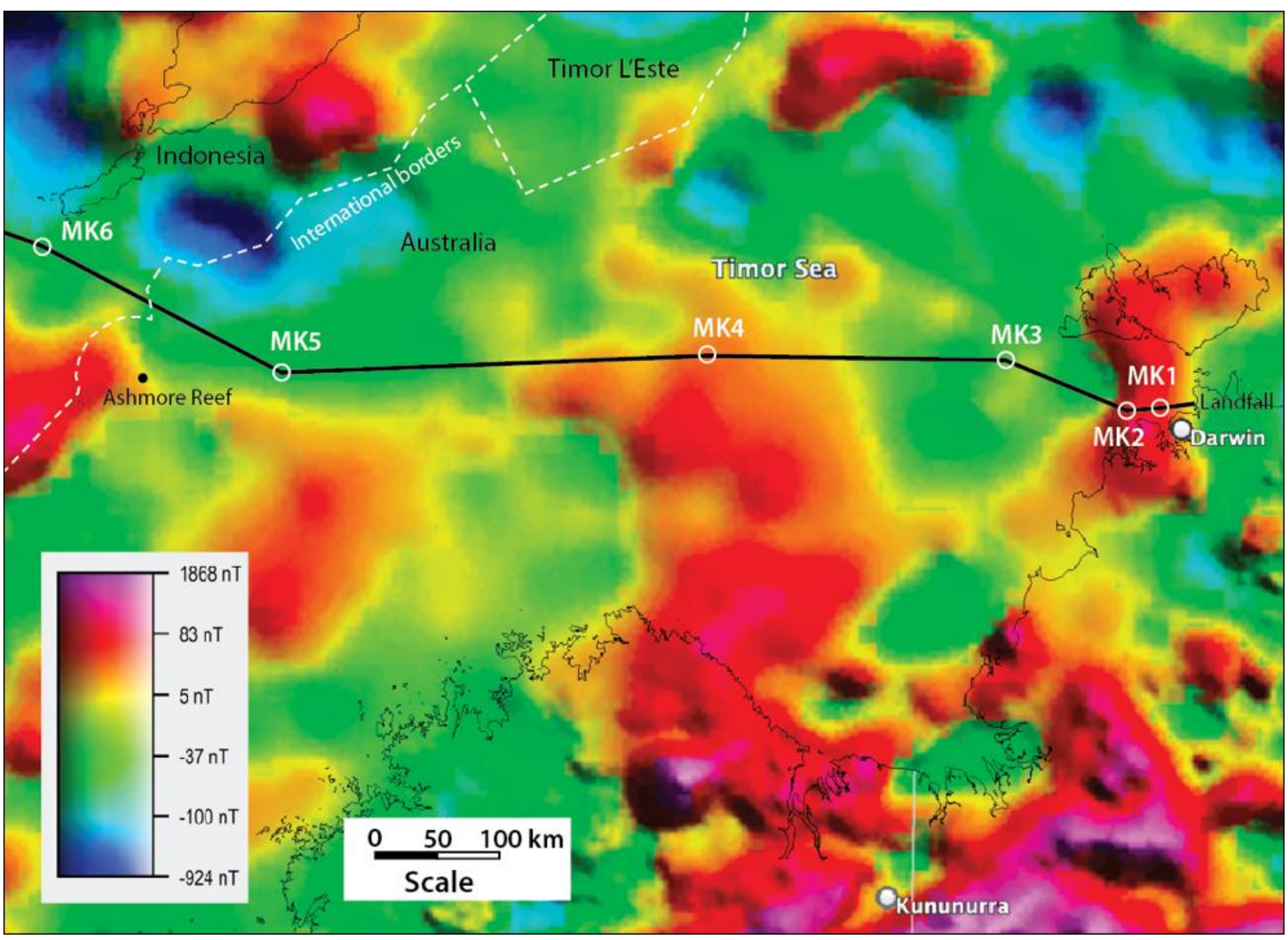
Magnetic anomalies are defined as the vector or scalar difference between the measured magnetic field and an estimate of the main field and are commonly assumed to reflect the magnetic properties of rocks lying in the Earth's crust (Thébault, 2014).

Figure 4.2 shows a magnetic anomaly map of the Proposal's nearshore study area (i.e., Shoal Bay and Beagle Gulf) and Figure 4.3 shows a magnetic anomaly map of the Proposal's offshore study area (i.e., Timor Sea). These anomaly maps describe the average variation in the ambient geomagnetic field at a moment in time due to variations in the core and lithospheric fields.



Source: NOAA (2017). Black line denotes approximate alignment of Sun Cable Subsea Cables Systems (Route Option B). Marker locations (MK 1 and MK 2 in Table 4.1) are nearshore EMF modelling points based on Norman (2022).

Figure 4.2: Nearshore magnetic anomaly map of Shoal Bay and the Beagle Gulf



Source: NOAA (2017). Black line denotes approximate alignment of Sun Cable Subsea Cables Systems. Marker locations (MK 3 through MK 5 in Table 4.2) are offshore EMF calculation points based on Norman (2022).

Figure 4.3: Offshore magnetic anomaly map of Timor Sea along cable route

The magnetic anomaly maps are derived from satellites, ships, and airborne measurements taken by aircraft and describe anomalies above and below a nominal, ambient geomagnetic field. These magnetic anomalies are a result of geologic features enhancing or depressing the local geomagnetic field. In general, magnetic anomalies typically consist of gradients of around 0.01 – 0.1 µT/km (Skiles, 1985).

The steady-state geomagnetic field along the nearshore subsea cable route within Shoal Bay and the adjoining Beagle Gulf varies by about +0.083/-0.037 µT due to the magnetic anomalies. Whereas the steady-state geomagnetic field along the offshore Subsea Cable Systems route within Commonwealth marine waters from the NT three nautical mile limit to the Australian-Indonesian maritime border in the Timor Sea varies by about +0.05/-0.037 µT due to magnetic anomalies.

4.3 Existing background electric fields

4.3.1 Natural electric fields in the sea

Knowledge of the existing natural electric fields in the Beagle Gulf and Timor Sea is required for comparison with induced electric fields associated with seawater (an electrolyte) flows or marine animals moving through the vertical component of the Proposal-generated magnetic fields.

The horizontal movement of seawater through the vertical component of the geomagnetic field or Proposal-generated magnetic fields creates an induced electric field.

Existing natural electric fields

In general, natural electric fields in the sea or ocean normally range from 0.5 to 50 µV/m (Kalmijn, 1999). The updated literature review did not reveal any measurements of naturally occurring electric fields specific to the Beagle Gulf or Timor Sea. However, estimates of background natural electric fields in nearshore and offshore Proposal areas can be calculated using the following equation as used by Sherwood et al. (2016):

$EF = MF_{VC} \times V$

where E is the electric fields (µV/m), MF_{VC} is the vertical component of the geomagnetic field (µV/m), and V is the velocity (m/s) of tidal or bottom currents flowing horizontally through the MF_{VC}.

Calculated natural electric fields in nearshore NT waters

Due to the macro-tidal regime of the Beagle Gulf and surrounding waters, prevailing currents are of tidal origin (Williams et al., 2006) and maximum flood current speeds may vary from 0.3 m/s (neaps) to 1 m/s (springs), while maximum ebb current speeds may vary from 0.5 m/s (neaps) to 1.6 m/s (springs).

Based on the full range of current flows (0.3 to 1.6 m/s) and the vertical component of the magnetic field of 29.2 µT at Marker 1 (see Table 4.1), the background range of the natural electric field ranges from 8.76 µV/m to 46.72 µV/m in the Beagle Gulf. This range can then be compared with the induced electric fields caused by seawater flow through the vertical component of the Proposal's HVDC cable-generated magnetic fields.

Calculated natural EFs in offshore Commonwealth Marine waters

The current offshore Proposal area within the Timor Sea is complex with the presence of large-scale currents dominated by the Indonesian Throughflow (Collins, 2010) with average speeds of between 0.2 and 0.4 m/s (Draft EIS) or 0.5 m/s (SKM, 2002). The latter average speed of 0.5 m/s has been used in the subsequent calculations of induced Efs.

Based on the vertical components of the geomagnetic fields at Markers 3, 4 and 5 (see Table 4.2) and using the average current speed of 0.5 m/s, the estimated average natural induced electric field for Markers 3, 4 and 5 is 14.43 µV/m. Therefore, an average background natural EF of 14.43 µV/m has been adopted as representative of the Timor Sea.

Existing anthropogenic electric fields

Electric fields can also be generated by ship movement (Rannou and Coulomb 2006; Nakamura et al., 2006). However, these fields are weak and not significant to the marine ecosystem.

Direct electric fields are also generated along oil and gas subsea pipelines that have cathodic protection systems. Cathodic electrochemical protection of an underground or subsea pipeline slows down the rate of corrosion of the metal piping by shifting the electrical protective potential at the pipe/soil boundary to a predetermined interval at which the oxidative processes in metal are reduced (Krizsky et al, 2021). The main existing oil and gas field pipelines in Beagle Gulf are the Santos Bayu-Undan to Darwin gas pipeline and the Ichthys LNG gas export pipeline, which will be crossed by the proposed alignment of the Proposal's Subsea Cable Systems.

Bioelectric fields

In addition, to natural induced electric fields in the sea generated by the movement of seawater or a marine animal through the geomagnetic field, all living marine organisms constantly generate DC and AC electric fields naturally (Crampton, 2019). However, these bioelectric fields are generally weak and are derived from muscle activity such as respiratory movements, cardiac contractions and locomotion, as well as the electrochemical difference between the organism's internal environment and the surrounding seawater (Gill and Taylor, 2001). Characteristics of the biogenic electric fields depend on the taxonomic group, position and activity of the organism, but typically range from 2 to 100 µV/cm (2,000 to 100,000 nV/cm) at a very close distance (Haine et al., 2001). For example, AC fields are emitted due to heart activity and muscle contractions, while DC fields occur due to biochemical processes in the body (Olsson et al, 2010).

Table 4.3 lists measured electric field sensitivities of various elasmobranchs and includes the distances at which the electric fields were detected (Bedore and Kajiura, 2013).

Table 4.3: Electric field sensitivity and distance of detection by elasmobranchs

Species	Common name	Electric field (nV/cm)	Detection distance (cm)	Reference
Squalus acanthias	Piked dogfish	14	30	Jordan et al. (2011)
Mustelus canis	Dusky smooth-hound	29	26	Jordan et al. (2011)
Urobatis halleri	Round stingray	29	40	Jordan et al. (2009)
Myliobatis californica	California bat ray	48	40	Jordan et al. 2009
Pteroplatytrygon violacia	Pelagic stingray	40	30	Jordan et al. 2009
Dasyatis sabina	Atlantic stingray	5	44	McGowan and Kajiura 2009
Sphyrna tiburo	Bonnethead shark	47	22	Kajiura 2003
Carcharhinus plumbeus	Sandbar shark	30	32	Kajiura and Holland 2002
Sphyrna lewini	Scalloped hammerhead	25	31	Kajiura and Holland 2002

Source: Bedore and Kajiura (2013).

Bedore and Kajiura (2013) measured the magnitude and frequency of the electric field produced by 11 families of marine organisms and found that marine invertebrate electric potentials ranged from 14 to 28 µV and that of elasmobranchs (sharks, rays and skates) ranged from 18 to 30 µV.

The abovementioned weak bioelectric fields can be readily detected by the highly sensitive electrosensory systems (ampullar of Lorenzini). A key point here is that the electrosense of elasmobranchs use a close-quarter sensory system mainly within the range of 15 to 50 cm and at greater distances (e.g., > 1 m) elasmobranchs are unlikely to be capable of detecting the bioelectric potentials surrounding prey organisms (e.g., fishes or marine invertebrates partially buried in sandy seabed).

4.4 Predicted Proposal-generated magnetic fields

The Proposal's generation of magnetic fields is dependent on cable configuration, whether the HVDC cables are installed within the seabed or laid directly on the seabed and with or without rock placement, and variability in power transfer and voltage.

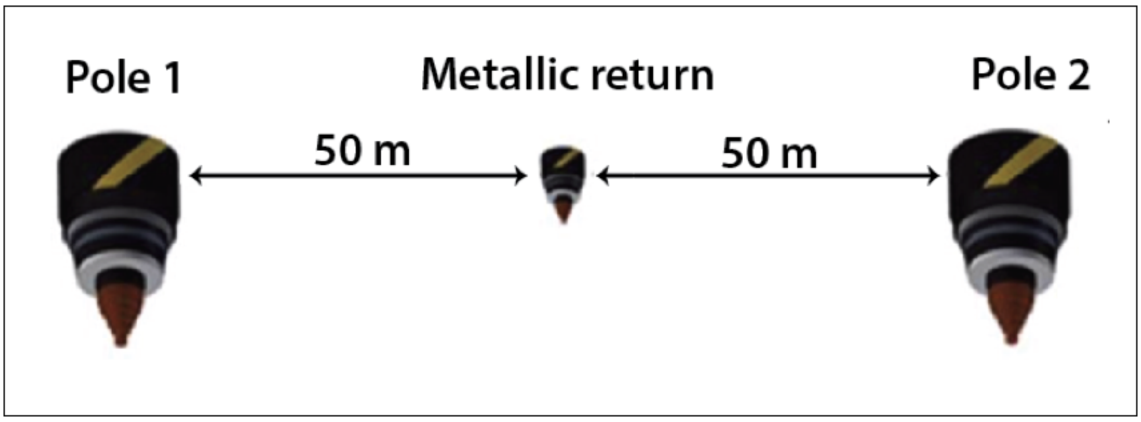
4.4.1 Cable Configurations

The Proposal's first stage subsea cable system comprises two 525 kV rated HVDC cables and a lower voltage metallic return cable. The cables will be installed and commissioned in two phases: before and after full commissioning. Before full commissioning, electric current will flow in the Pole 1 and a metallic return cable. When the system is fully commissioned (i.e., Pole 2 has been installed), electric current will flow in the Pole 1 and Pole 2 cables. Only two cables will carry current at any one time. In the second stage of the Proposal, another two poles and a MER may be constructed in parallel with the first stage of the Proposal. This impact assessment is for the first stage, however the findings are also applicable to the second stage, as each stage will be separated and EMF interaction between the two stages is not predicted.

The cables may be installed in two standard configurations: a spaced configuration and a bundled configuration. These are described below.

Spaced cable configuration

The spaced cable configuration where individual cables are laid and spaced at least 50 m apart is shown in Figure 4.4 below.

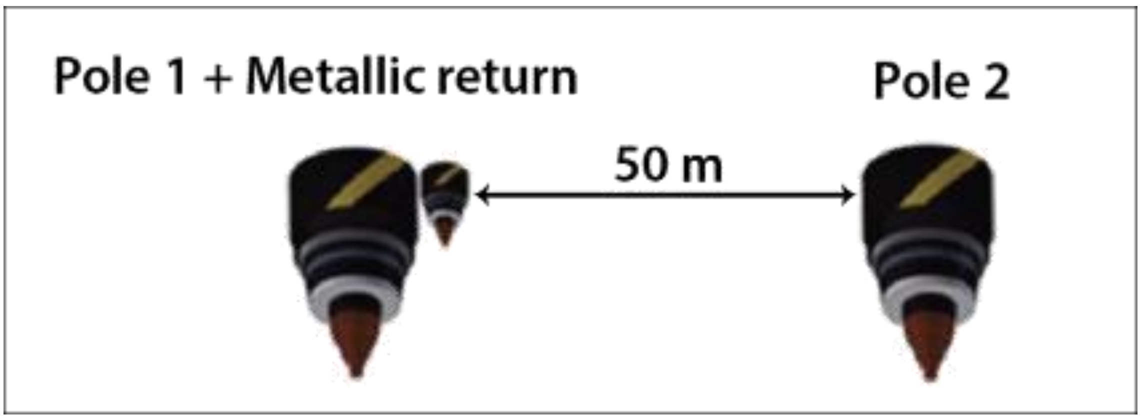


Source: Sun Cable (2022).

Figure 4.4: Spaced cable configuration

Bundled Cable Configuration

The bundled cable configuration is shown in Figure 4.5 in which the Pole 1 HVDC cable would be bundled with the metallic return cable, whereas Pole 2 would be installed separately during the full commissioning phase. A separation distance of at least 50 m would be used between the bundled cable (Pole 1 and metallic return cable) and the separate Pole 2 cable. Where HVDC cables are spaced at least 50 m apart, the interaction between the two HVDC cables at any specific point of interest will be minimal and can be ignored.



Source: Sun Cable (2022).

Figure 4.5: Bundled cable configuration

The currents that flow in the bundled HVDC (Pole 1) and metallic return cable flow in opposite directions and this results in some cancelling of the net magnetic field at any specific point of interest. In contrast, in the spaced cable configuration, the HVDC cables are at least 50 m apart and, therefore, the net magnetic field cancelling effect is negligible. For this reason, Notman (2022) performed EMF calculations for the worst case of a spaced HVDC cable in isolation. See Table 4.5 below for the maximum total magnetic field intensities (i.e., the combined geomagnetic and cable-generated magnetic fields) for cables laid directly on the seabed or buried in the seabed to -1 m.

Mode of cable installation

Spaced or bundled cables may be either buried in seabed sediments or laid directly on the seabed. In the case where the cables need to be buried (e.g., to avoid anchor hook-ups or bottom-trawled fishing gears) a burial depth of -1 m in soft-sediment seabed (e.g., sands and muds) has been assumed, since this is the typical burial depth that has been used by other HVDC cable projects within Australia's continental shelf (e.g., the Basslink subsea cable in Bass strait and a currently proposed second subsea HVDC cable crossing of Bass Strait) and at overseas HVDC subsea cables.

As-laid cable circuit orientation

The orientation of the as-laid cable circuits will affect the resultant total magnetic field (i.e., combined cable magnetic field and geomagnetic field), which is influenced by the following cable circuit angles (Notman, 2022).

- 0° The cables run north to south.
- 45° The cables run northeast to southwest.
- 90° The cables run east to west.
- -45° The cables run northwest to southeast.

For this assessment, a cable circuit angle of 90° has been selected given that the Proposal's subsea cables systems mainly run in an east-west direction in both the nearshore NT waters and the offshore Commonwealth Marine waters.

EMF modelling conditions

Notman (2022) calculations have been performed at the 21 marker locations for the cable burial depths and configurations, including the five marker locations in Australian waters (i.e., Marker 1 through 5). Calculations by Notman (2022) were performed in three stages: a) the geomagnetic field, b) the cables' magnetic fields, and c) the resultant magnetic field (i.e., the combined cable and geomatic field).

The modelled magnetic field is presented here and represents the predicted magnetic field that marine fauna may be exposed to. For each set of inputs, Notman (2022) only calculated the resultant magnetic fields at seabed level and 1 m above seabed level.

Table 4.4 shows the modelling conditions for cable configurations and cable burial depths at EMF modelling locations (i.e., markers) (Notman, 2022). The cable burial depths denote burial depths to the top of the cable below the seabed. Cable burial depth of '0 m' denotes that the cable is laid directly on the seabed.

Table 4.4: EMF modelling conditions

Case	Cable configuration	Modelled EMF Location	Cable burial depth	Reference height at seabed	Reference height above seabed	Loading per cable	Cable circuit angle
Nearshore NT waters:							
Case A1	Spaced	Marker 1	-1 m	0 m	1 m	1,950 A	90°
Case B1	Bundled	Marker 1	-1 m	0 m	1 m	683 A	90°
Case A2	Spaced	Marker 1	0 m	0 m	1 m	1,950 A	90°
Case B2	Bundled	Marker 1	0 m	0 m	1 m	863 A	90°
Offshore Commonwealth waters:							
Case D	Bundled	Marker 4	-1 m	0 m	1 m	683 A	90°
Case E	Spaced	Marker 5	0 m	0 m	1 m	1,950 A	90°

Source: Notman (2022).

Predicted Proposal-generated EMFs

The Proposal's cable EMFs were modelled by Notman (2022) at EMF modelling sites within nearshore NT waters (Beagle Gulf) at Marker 1, and within offshore Commonwealth waters (Timor Sea) for Markers 4 and 5. Table 4.5 shows the maximum total magnetic field intensities (i.e., the combined geomagnetic and cable-generated magnetic fields) for cables laid directly on the seabed or buried in the seabed to -1 m. The total magnetic intensities are calculated at a cable's outer surface, at the seabed, and 1 m above the seabed.

Table 4.5: Background geomagnetic field and maximum combined total magnetic intensities

Marker	Background Geomagnetic field (µT)	Maximum combined total magnetic field intensities (µT)							
		Cable on seabed surface				Cable buried to 1 m			
		Cable surface	Difference (%)	1 m above cable	Difference (%)	Seabed surface	Difference (%)	1 m above seabed	Difference (%)
Bundled cable configuration:									
1	46.158	1,726.5	3640.4	62.8	36.1	62.8	36.1	50.6	9.6
3	46.062	1,726.1	3647.3	62.7	36.1	62.7	36.1	50.5	9.6
4	46.137	1,726.0	3641.0	62.7	35.9	62.7	35.9	50.6	9.7
Spaced cable configuration:									
1	46.158	4,880.5	10473.5	398.5	763.3	398.5	763.3	226.4	390.5
3	46.062	4,880.7	10495.9	398.7	765.6	398.7	765.6	226.5	391.7
4	46.137	4,880.9	10479.1	398.8	764.4	398.8	764.4	226.7	391.4
5	46.372	4,881.0	10425.7	398.9	760.2	–		–	

Source: Notman (2022). Marker 2 is not shown as the cable burial depth is -2 m depth due to presence of sand megaripples. The light blue shaded cells have been adopted to assess EMF impacts on marine fauna (as explained below). Data in the table are for a cable circuit angle of 90° (i.e., an east-west orientation).

Adopted cable EMF scenarios for impact assessment

Three scenarios have been adopted for the EMF impact assessment:

Scenario 1 – bundled HVDC/metallic return cable buried to -1 m depth at Marker 1 in the Beagle Gulf.

Scenario 2 – spaced HVDC cable buried to -1 m depth at Marker 1 in the Beagle Gulf.

Scenario 3 – spaced HVDC cable laid on seabed at Marker 5 in the Timor Sea.

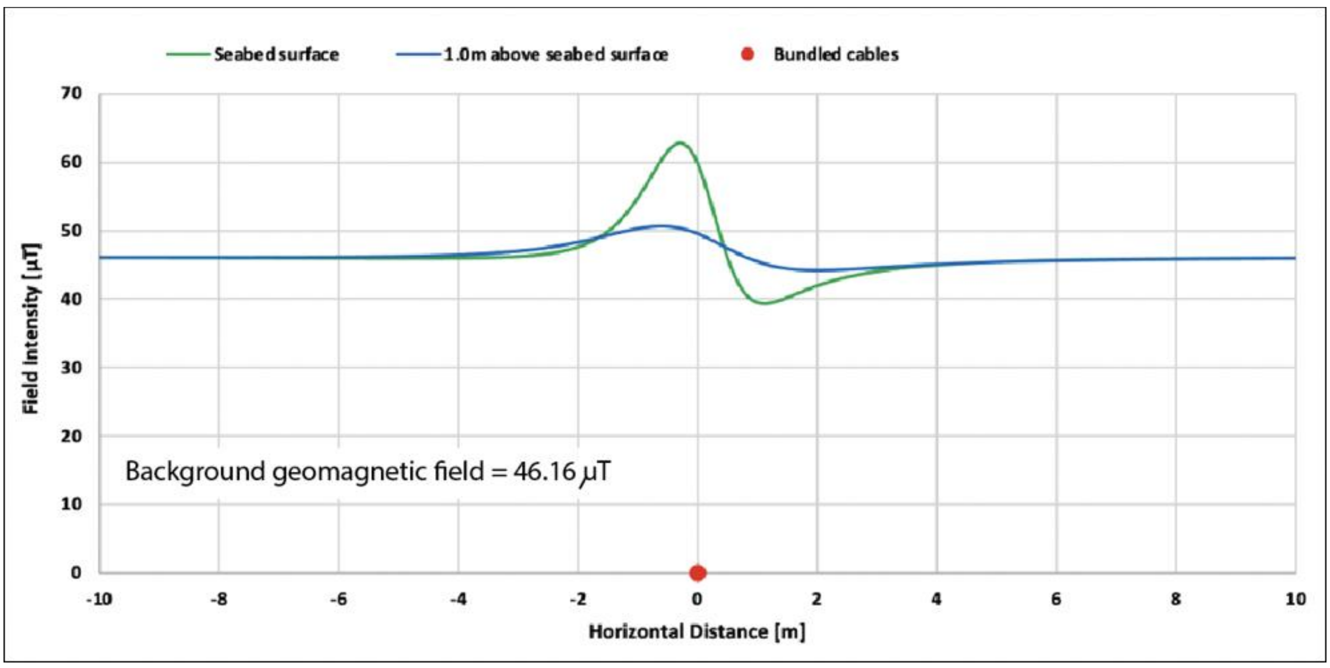
Scenario 1 – Buried bundled cable, nearshore

EMF calculations for the bundled cable configuration represents the bundled HVDC cable (Pole 1) and metallic return cable at EMF modelling location Marker 1, which may be carried out during Phase I of the Proposal prior to installation of the second HVDC cable (Pole 2) during Phase II of the Proposal. Pole 2 has not been included in the calculations as the resultant geomagnetic field from Pole 1 would not interact with the resultant magnetic field of Pole 2 due to the separation distance of at least 50 m.

Under Scenario 1, the following total maximum field intensities (combined cable-generated and geomagnetic fields) have been adopted for subsequent impact assessment:

- 62.8 µT at the seabed surface overlying the buried bundled cable's location (based on Table 4.5).
- 50.6 µT at 1 m above the seabed surface (based on Table 4.5).

Figure 4.6 shows the combined maximum total magnetic intensity for EMF modelling site Marker 1 in Beagle Gulf. In Figure 4.6, the maximum total magnetic field intensity is 62.8 µT at the seabed (0 m) and 50.6 µT at 1 m above the seabed, and the background geomagnetic field is 46.16 µT at Marker 1 in the Beagle Gulf.



Source: Notman (2022; see attached Appendix 2 of this assessment).

Figure 4.6: Combined total magnetic intensity for bundled cable buried to -1 m depth

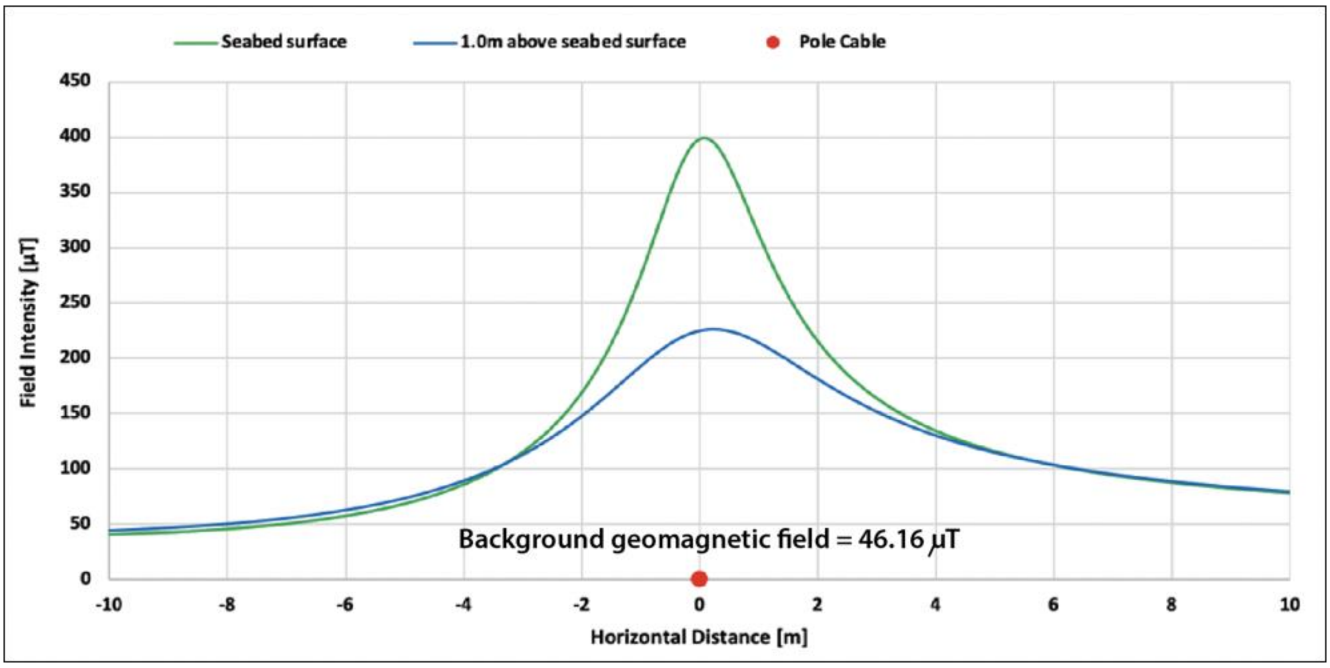
Scenario 2 – Buried spaced HVDC cable, nearshore

EMF calculations for a spaced cable configuration represents a single HVDC cable buried to -1 m depth in soft-sediment seabed at EMF modelling location Marker 1. This scenario may eventuate during Phase I of the Proposal prior to installation of the second HVDC cable (Pole 2) during Phase II of the Proposal. Pole 2 has not been included in the calculations as the resultant geomagnetic field from Pole 1 would not interact with the resultant magnetic field of Pole 2 due to the separation distance of at least 50 m.

Under Scenario 2, the following the total maximum field intensities (combined cable-generated and geomagnetic fields) have been adopted for subsequent impact assessment:

- 398.5 µT at the seabed surface overlying the buried spaced cable's location (based on Table 4.5).
- 226.4 µT at 1 m above the seabed surface (based on Table 4.5).

Figure 4.7 shows the combined total field intensity at EMF modelling site Marker 1 in the Beagle Gulf. The maximum total magnetic field intensity is 398.5 µT at the seabed (0 m) and 226.4 µT at 1 m above the seabed, and the background geomagnetic field is 46.16 µT at Marker 1 in the Beagle Gulf.



Source: Notman (2022; see Appendix 2 of this assessment).

Figure 4.7: Combined total magnetic intensity for spaced HVDC cable buried to -1 m depth

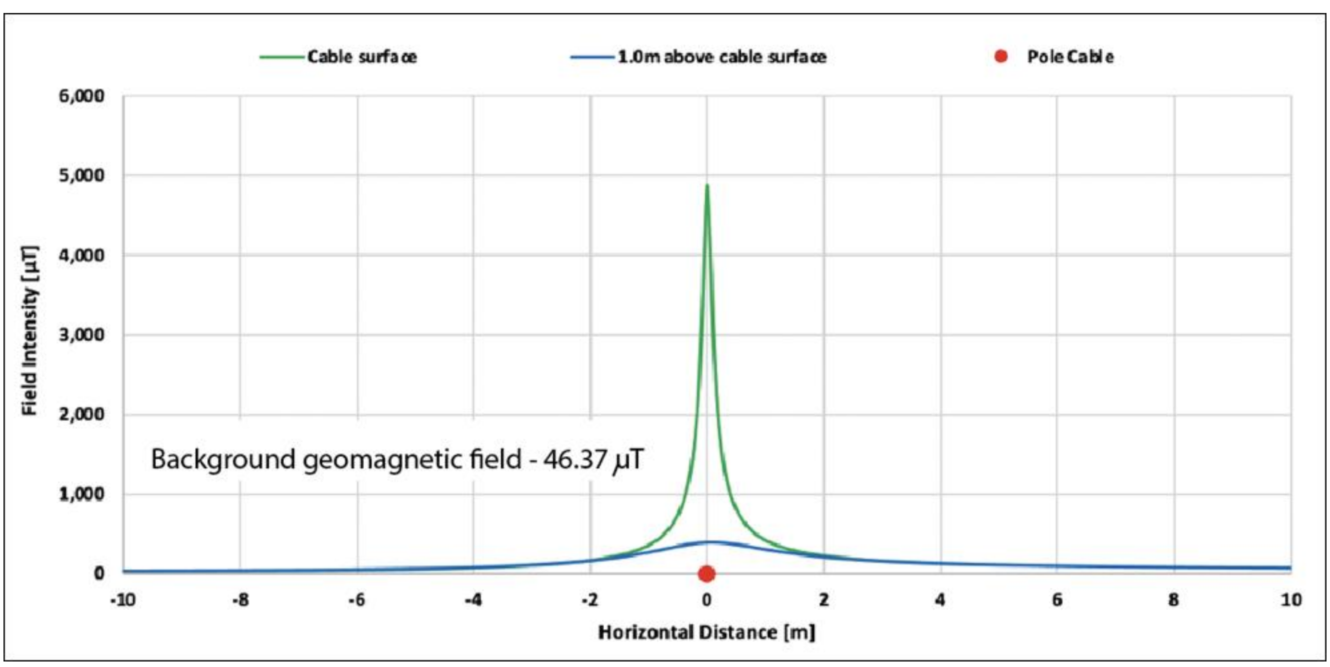
Scenario 3 – Unburied spaced HVDC cable, offshore

Scenario 3 is based on EMF calculations for the spaced cable configuration and represents the worst-case scenario of a spaced HVDC cable (Pole 1) in isolation and assumes that the cable is laid directly on the seabed (i.e., exposed) at Marker 5 (see Table 4.5).

Under Scenario 3, the following total maximum field intensities (combined cable-generated and geomagnetic fields) have been adopted for subsequent impact assessment:

- 4,881 µT at the cable's exposed external surface (based on Table 4.5), which includes the background geomagnetic field of 46.37 µT (based on Table 4.2).
- 398.9 µT at 1 m above the cable[1]/seabed surface (based on Table 4.5), which includes the background geomagnetic field of 46.37 µT (based on Table 4.2).

Figure 4.8 shows the combined total field intensity at EMF modelling site Marker 5 (117 km west of Ocean Shoals Marine Park).



Source: Notman (2022; see Appendix 2 of this assessment).

Figure 4.8: Combined total magnetic intensity for spaced HVDC cable laid on the seabed

In Figure 4.8, the base of the cable's magnetic field is about 1.5 m wide rising as a sharp peak to the maximum intensity of 4,881.0 µT, whereas in the horizontal direction the cable's magnetic field rapidly reduces to the background geomagnetic total intensity level of around 46.37 µT within about 10 m. The EMF report by Notman (2022), only presented one vertical data point (i.e., at 1 m above seabed); therefore, the reduction of the EMF with vertical distance to where background EMF is reached cannot be reported. Modelled horizontal distances

[1] The height of the HVDC cable (0.14 m diameter) is ignored given that the cable may sink in soft sediments due to its weight.

have been used as a surrogate for the magnetic field as it reduces with vertical distance, which is an approximation given that both the vertical and horizontal axes are perpendicular to the cable.

Comparison of the Proposal with other HVDC subsea cable systems

A comparison of the Proposal's predicted HVDC cable's total magnetic fields with other subsea HVDC cable systems has been undertaken. Each subsea cable system has a different current rating and a different background geomagnetic total magnetic intensity. Table 4.6 presents data showing total magnetic fields (i.e., the combined HVDC cable and geomagnetic field) at the seabed or 1 m above the seabed.

Comparison with buried cable configurations

Table 4.6 summarises available information on HVDC subsea cables for which predicted or measured maximum combined total magnetic fields were available. In all cases, the HVDC cables were buried within a spaced or bundled configuration. The combined total magnetic field at 1 m above the seabed for the original Basslink configuration (i.e., spaced HVDC cable and sea electrodes) was calculated to be 218.3 μT (NSR, 2002), which is of the same magnitude as the 226.4 μT at 1 m above the seabed calculated for the Proposal's spaced HVDC cable buried to -1 m depth at Marker 1 in the Beagle Gulf (Scenario 2). The combined total magnetic field at 1 m above the seabed for the Basslink's adopted bundled cable configuration (i.e., HVDC cable plus metallic return cable) was calculated to be 84.4 μT (NSR, 2002), which is of similar magnitude as the 50.6 μT at 1 m above the seabed calculated for the Proposal's bundled cable buried to -1 m depth at Marker 1 in the Beagle Gulf (Scenario 1) – see Table 4.6.

Table 4.6: Combined Total Magnetic Field Comparison with Buried Cable Configurations

HVDC Subsea Cables	Cable Configuration	Burial Depth (m)	Combined Total Magnetic Field (µT)	Geomagnetic Background (µT)	Current Proposal Prediction		
					Cable Configuration	Combined Total Magnetic Field (µT)	Geomagnetic Background (µT)
Basslink (Australia)	The original subsea cable system was a monopolar configuration with a spaced HVDC cable and sea electrodes	1	218.3 at 1 m above the seabed	61.0	Spaced HVDC cable and separate MER (Marker 1)	226.4 at 1 m above the seabed	46.16
Basslink (Australia)	The final adoption was a monopolar configuration with a bundled HVDC cable and MER configuration	1	84.4 at 1 m above the seabed	61.0	Bundled HVDC cable and MER (Marker 1)	50.6 at 1m above the seabed	46.16
Cross Sound Cable (USA)	Bipolar configuration comprising of two bundled HVDC Light cables and has a maximum transmission power of 330 MW, 300 kV voltage rating, and a maximum current rating of 1,175 A	Average of 1.5 (range 1.2–1.8)	66.0 at the seabed	51.3	Bundled HVDC cable and MER (Marker 1)	62.8 at the seabed	46.16
Neptune Cable (USA)	Monopolar configuration comprising of a bundled HVDC cable and MER and has a maximum transmission power of 600 MW, 500 kV voltage and current of 1,320 A	Average of 1.4	72.0 at the seabed	51.3	Bundled HVDC cable and MER (Marker 1)	62.8 at the seabed	46.16

Sources : (NSR, 2001), (Notman, 2022), (Hutchison et al., 2021).

Comparison with non-buried HVDC cable surface magnetic fields

A review of the predicted or measured magnetic fields on HVDC cable surfaces did not reveal relevant values for comparison with Scenario 3 (spaced HVDC cable laid on the seabed (i.e., unburied) at EMF modelling sites Marker 5), as cables are typically buried for cable protection from anchor hook-ups and bottom trawling fishing gear. The nearest approximation is for the Basslink HVDC cable that was encased in cast iron half-shells and laid on hard seabed in nearshore Tasmania.

Table 4.7 presents maximum magnetic fields on the surface of HVDC cables and at similar distances from the cable for other subsea cable systems. This can be described with a knowledge of the current flowing in the HVDC cable and the cable's radius. Magnetic flux density ('B') is a measure of magnetic interaction which uses the Biot-Savart Law, where 'I' is the current, 'μ' is the magnetic permeability of the medium, and 'r' is the radial distance from the current axis. The equation is expressed as follows: $B = (\mu I)/(2\pi r)$.

Table 4.7 presents a summary of HVDC cable total magnetic fields and the distances at which the cable magnetic fields approach the local background geomagnetic total magnetic field intensity, which are highlighted in grey shading.

Table 4.7: Comparison of Proposal HVDC cable magnetic fields with other subsea HVDC cable systems

HVDC scheme	Cable radius (mm)	Burial depth (m)	Calculated point at cable surface and at different heights	Cable MF at distance (μT)	Background GMF (μT)
AAPowerLink (Proposal) 900 MW (initially) 525 kV 683 A Bundled cable (buried) at Marker 1 (east-west, 90 ° alignment) (Scenario 1)	80.5	1.0	Cable surface 0 m (seabed) 0.5 m above seabed 1 m above seabed 2 m above seabed 2.96 m above seabed 3 m above seabed 5 m above seabed 10 m above seabed	1,696.9 136.6 91.7 68.3 45.53 46.16 34.15 22.77 12.42	46.16 46.16 46.16 46.16 46.16 46.16 46.16 46.16 46.16
AAPowerLink (Proposal) 900 MW (initially) 525 kV 1,950 A Spaced cable (buried) at Marker 1 (east-west, 90 ° alignment) (Scenario 2)	80.5	1.0	Cable surface 0 m (seabed) 0.5 m above seabed 1 m above seabed 2 m above seabed 3 m above seabed 5 m above seabed 7.45 m above seabed 10 m above seabed	4,844.7 390.0 260.0 195.0 130.0 97.5 65.0 46.16 43.3	46.16 46.16 46.16 46.16 46.16 46.16 46.16 46.16 46.16
AAPowerLink (Proposal) 900 MW (initially) 525 kV 1,950 A Spaced cable (unburied) at Marker 5 (east-west, 90 ° alignment) (Scenario 3)	80.5	0.0	Cable surface 0 m (seabed) 0.5 m above seabed 1 m above seabed 2 m above seabed 3 m above seabed 5 m above seabed 8.41 m above seabed 10 m above seabed	4,844.7 4,844.7 780.0 390.0 195.0 130.0 78.0 46.37 39.0	46.37 46.37 46.37 46.37 46.37 46.37 46.37 46.37 46.37
Basslink 600 MW 400 kV 1,500 A Spaced HVDC cable and earth return (north-south, 0° alignment)	75.0	1.0	Cable surface 0 m (seabed) 0.5 m above seabed 1 m above seabed 2 m above seabed 3 m above seabed 4.92 above seabed 5 m above seabed 10 m above seabed	4,000.0 300.0 600.0 150.0 100.0 75.0 61.0 50.0 27.3	61.0 61.0 61.0 61.0 61.0 61.0 61.0 61.0 61.0
Basslink 600 MW 400 kV NR A Bundled cable in half-shells (unburied) in Tasmania (north-south, 0° alignment) (Combined bundled cable plus background geomagnetic field)	75.0	0.0	Cable surface 0 m (seabed) 0.5 m above seabed 1 m above seabed 2 m above seabed 10 m above seabed 20 m above seabed	NR NR NR 81.4 62.3 61.6 61.6	61.6 61.6 61.6 61.6 61.6 61.6 61.6

Notes: NR denotes Not Reported. Data sources: Basslink (NSR, 2002) and Proposal (Notman, 2022).

In Table 4.7, the spaced HVDC cables buried to -1 m for the Basslink original cable configuration revealed that the total magnetic field decreased to the background geomagnetic field of 61.0 μT at a distance of 4.92 m above the seabed, whereas the Proposal's spaced HVDC cable buried to -1 m (Scenario 2) decreased to the background geomagnetic field strength of 46.16 μT at a distance of 7.45 m. The distance it took to decrease the total magnetic fields to the background geomagnetic field strength are of similar magnitude. In all the buried or unburied subsea cable systems, the spaced or bundled cables' total magnetic fields decreased to background geomagnetic fields within 10 m.

Given the Proposal's maximum predicted MF of 4,844.7 μT for the offshore unburied spaced configuration at the cable surface (Notman, 2022), this has been rounded to 4,800 μT for comparison with the magnetic fields of cable surfaces for other subsea HVDC cable systems and/ or levels tested in laboratory experiments such as:

4,800 μT – Notman (2022; Appendix 2 of this assessment).

3,700 μT – Bochert and Zettler (2004).

3,500 μT – Schultz et al. (2010).

2,800 μT – Scott et al. (2018)

2,800 μT – Harsanyi et al. (2022).

2,300 μT – Schultz et al. (2010).

The Proposal's predicted MF intensity of 4,800 μT at the cable surface is at the top range compared to other HVDC cables (range 2,300 to 3,700 μT), which is mainly due to the higher current 1,950 A, since earlier single subsea HVDC cables up to 2015 typically had maximum currents in the range 1,000 to 1,500 A.

4.5 Predicted Proposal induced electric fields

Calculation of the induced electric fields surrounding the Proposal's energised HVDC cables, requires a knowledge of the vertical component of the resultant total magnetic field at the cables. Although the data provided by Notman (2022) did not provide calculations showing the vertical component of the resultant total magnetic field (i.e., combined cable and natural magnetic field) for the Proposal's energised cables the vertical component is typically around 63% of the total magnetic field. This percentage has been applied to obtain gross estimates of the vertical component of the resultant total magnetic field for this assessment.

Induced electric fields were calculated for Scenario 1 (1-m buried bundled cable in the Beagle Gulf at Marker 1), Scenario 2 (1-m buried spaced cable in the Beagle Gulf at Marker 1), and Scenario 3 (unburied spaced HVDC cable at Marker 5 in the Timor Sea), which are summarised in Table 4.8 and described below.

4.5.1 Scenario 1 – Nearshore induced electric fields in the Beagle Gulf

Induced electric fields have been calculated at the seabed and 1 m above the seabed for the EMF modelling site (Marker 1) in the Beagle Gulf for Scenario 1 (bundled HVDC/metallic return cable buried to -1 m depth).

Predicted induced electric fields at the seabed

Based on the range of flood and ebb tidal current flows (0.3 to 1.6 m/s) in the Beagle Gulf (Williams et al., 2006), electric fields induced by horizontal seawater flow through the predicted vertical component (39.7 μT) of the resultant total magnetic field (62.8 μT) at the seabed are calculated to be 11.9 μV/m and 63.4 μV/m for a current flow of 0.3 m/s and 1.6 m/s, respectively. The predicted induced electric fields at the seabed are of similar magnitude as the natural background induced electric fields 8.76 μV/m to 46.72 μV/m for the same current flows of 0.3 m/s and 1.6 m/s, respectively.

Predicted induced electric fields at 1 m above the seabed

Based on the range of flood and ebb tidal current flows (0.3 to 1.6 m/s) in the Beagle Gulf (Williams et al., 2006), electric fields induced by horizontal seawater flow through the predicted vertical component (31.9 μT) of the total magnetic field (50.6 μT) at 1 m above the seabed are calculated to be 9.5 μV/m and 51.0 μV/m for a current flow of 0.3 m/s and 1.6 m/s, respectively. The predicted induced electric fields at 1 m above the seabed are of similar magnitude as the natural background induced electric fields of 8.76 μV/m to 46.72 μV/m for the same current flows of 0.3 m/s and 1.6 m/s, respectively.

4.5.2 Scenario 2 – Nearshore induced electric fields in the Beagle Gulf

Induced electric fields have been calculated at the seabed and 1 m above the seabed for the EMF modelling site (Marker 1) in the Beagle Gulf for Scenario 2 (i.e., spaced HVDC cable buried to -1 m depth in soft-sediment seabed).

Predicted induced electric fields at the seabed

Based on the range of flood and ebb tidal current flows (0.3 to 1.6 m/s) in the Beagle Gulf (Williams et al., 2006), electric fields induced by horizontal seawater flow through the predicted vertical component (251.0 μT) of the combined total magnetic field (398.5 µT) at the seabed are calculated to be 75.3 µV/m and 401.6 µV/m for a current flow of 0.3 m/s and 1.6 m/s, respectively. These predicted induced electric fields at the seabed are the same order of magnitude as the natural background induced electric fields (i.e., 8.76 µV/m) for the lower current flow of 0.3 m/s, but are predicted to be an order of magnitude higher (i.e., 401.6 µV/m) for the higher flow of 1.6 m/s.

Predicted induced electric fields at 1 m above the seabed

Based on the range of flood and ebb tidal current flows (0.3 to 1.6 m/s) in the Beagle Gulf (Williams et al., 2006), electric fields induced by horizontal seawater flow through the predicted vertical component (142.6 µT) of the combined total magnetic field (226.4 µT) at 1 m above the seabed are calculated to be 42.8 µV/m and 228.2 µV/m for a current flow of 0.3 m/s and 1.6 m/s, respectively. These predicted induced electric fields at 1 m above the seabed are the same order of magnitude as the natural background induced electric fields (i.e., 8.76 µV/m) for the lower current flow of 0.3 m/s, but are predicted to be an order of magnitude higher (i.e., 401.6 µV/m) for the higher flow of 1.6 m/s.

At other heights above the seabed of 2, 3, and 5 m the predicted induced electric fields at the lower seawater flow speed of 0.3 m/s are 30.9, 25.0, and 19.2 µV/m, respectively. Similarly, at the higher seawater flow of 1.6 m/s, the Proposal-generated induced electric fields at 2, 3, and 5 m above the seabed are predicted to be 165.1, 133.6 and 102.2 µV/m, respectively. These predicted induced electric field values are within the range of natural variability in background electric fields in the marine environment (Kalmijn, 1998; Randall et al., 1997).

4.5.3 Scenario 3 — Offshore induced electric fields in the Timor Sea

Induced electric fields have been calculated at the seabed and 1 m above the seabed for the EMF modelling site (Marker 5) in the Timor Sea.

Predicted induced electric fields at the seabed

Based on the average current speed of 0.5 m/s (SKM, 2002) in the Timor Sea in the vicinity of Marker 5, the electric field induced by horizontal seawater flow through the predicted vertical component (3,075 µT) of the resultant total magnetic field (3880.5 µT) at the seabed is 1,537 µV/m in the immediate vicinity of the unburied HVDC cable, which is 106-fold higher than the natural background electric field of 14.5 µV/m at the seabed of the same location. The induced electric field reduces to 242.0 µV/m at 0.5 m above the seabed.

Predicted induced electric field at 1 m above the seabed

Based on the average current speed of 0.5 m/s (SKM, 2002) in the Timor Sea in the vicinity of Marker 5, the electric field induced by horizontal seawater flow through the predicted vertical component (251.3 µT) of the resultant total magnetic field (398.9 µT) at 1 m above the seabed is 125.6 µV/m, which is 8.6-fold higher than the natural background electric field of 14.5 µV/m at the same location. These predicted induced electric field values are within the range of natural variability in background electric fields in the marine environment (Kalmijn, 1998; Randall et al., 1997).

Table 4.8: Summary of Predicted Proposal Induced Electric Fields

Scenario	Description	Predicted Induced Electric Fields (µV/m)	Natural Background Induced Electric Fields (µV/m)
Scenario 1	At the seabed	11.9 µV/m and 63.4 µV/m	8.76 µV/m to 46.72 µV/m
Scenario 1	1 m above the seabed	9.5 µV/m and 51.0 µV/m	8.76 µV/m to 46.72 µV/m
Scenario 2	At the seabed	75.3 µV/m and 401.6 µV/m	8.76 µV/m to 46.72 µV/m
Scenario 2	1 m above the seabed	42.8 µV/m and 228.20 µV/m	8.76 µV/m to 46.72 µV/m
Scenario 3	At the seabed	1,537 µV/m	14.5 µV/m
Scenario 3	1 m above the seabed	125.6 µV/m	14.5 µV/m

Note: Scenario 1 and 2 use seawater flows of 0.3 and 1.6 m/s (Williams et al., 2006). Scenario 3 uses a seawater flow of 0.5 m/s (SKM, 2002).

5 Environment Management Measures

5.1 Background

Under Item 4 in the Comment #15 (see Table 1.1), the NT EPA requested the following:

"Provide detail about how the proposed method of installing cables (laid on the seafloor, trenched into the seabed generally to a depth between 0.3 – 1 m or protected with armouring) would mitigate potential EMF impacts on marine fauna, and what post- installation verification is proposed."

The proposed main methods for installing the Proposal's cables are outlined in the Draft EIS and SEIS and include:

- Either buried cables or laid on the seabed.
- Bundled or spaced configuration.
- With or without rock protection.

Consistent with Section 26 of the *Environment Protection Act 2019,* the environmental decision-making hierarchy will be followed in order of priority: avoid, mitigate, and offset.

5.2 EMF mitigation measures through design

Measures to mitigate and reduce EMF are due to a secondary outcome of design and selected cable configuration. Design and cable configuration selection is driven by technical requirements and constraints, including sea depth, sea floor composure, and potential risks (e.g., risk of anchor strike). The principal direct or indirect EMF mitigation and/or reduction measures that could be considered during detailed design include:

- Direct mitigation by design (e.g., selecting modern cable designs).
- Direct mitigation by cable circuit configuration (e.g., bundling of HVDC cables).
- Indirect incidental mitigation by cable protection (e.g., burial in soft seabed or rock covers on hard seabed).

These measures, and any mitigation or reduction of EMF, would be subject to detailed design which would be completed to primarily meet technical requirements and constraints. The extent of adoption of these measures and locations would be confirmed during the detailed design process.

5.2.1 Direct mitigation by design

Due to improved insulation technology, high-voltage subsea power cables require less current to supply power than a cable of lower voltage, resulting in a reduction in their magnetic field emissions. The present Proposal intends to use modern cross-linked polyethylene (XLPE) cables such as those built by Prysimian.

Industry standards for subsea cables require shielding to block the electric field emitted using conductive sheathing (Boehlert and Gill, 2010). The electrical fields of HVDC cables are shielded by insulation and metallic armouring within the cables that are earthed at either end of the cables. Therefore, there is no direct electric field emitted outside the cable. However, magnetic induction causes indirect electric fields (called induced electric fields) outside of the cable, owing to the horizontal movement of seawater through the vertical component of an HVDC cable's magnetic field.

5.2.2 Direct mitigation by configuration

HVDC cables may be configured as spaced or bundled cables. Section 4.3.1 provides a description of each configuration and the potential total combined magnetic field cancellation properties associated with each. In summary:

- Spaced cable configurations beyond about 25m apart generally do not result in magnetic field cancellation.
- Bundled cable configurations - bundling two HVDC cables or bundling an HVDC cable with a metallic return cable results in a reduction to magnetic fields due to cancelling effect.

5.2.3 Indirect mitigation by cable installation depth

In many cases, especially in soft-bottom sediments (e.g., sands and muds), HVDC cables are buried to protect them from accidental potential hook-ups by ships' anchors and/or bottom-trawled fishing gear. A beneficial side effect of cable burial is a reduction of the maximum EMF at the seabed overlying the cable than would be the case of a cable laid directly on the seabed (i.e., unburied).

Cable burial is not regarded as a direct EMF mitigation measure and is generally only considered for technical reasons (e.g., to avoid anchor hook-ups in busy shipping areas). To date and based on the updated EMF literature review in Section 3, no proponents or operators of HVDC subsea cables have been required to bury cables for the primary purpose of reducing maximum EMFs at the seabed-water interface as a direct mitigation measure.

5.2.4 Indirect mitigation by rock cover of cables laid on the seabed

In many cases HVDC cables are laid directly on the seabed where cable burial is not possible (e.g., hard seabed). Within shipping areas, these cables are often either covered with loose rock (rock dumping) or concrete mattresses for protection against accidental hook-ups from ships' anchors or bottom trawled fishing gear. The rock cover or concrete mattresses reduces the maximum EMF at the rock/mattress cover-seawater interface. Given that burial depth using concrete mattresses would be around 1 m, the potential EMF effects would be similar to the EMF effects a cable buried into sediment to -1 m depth. Therefore, cable burial by rock mattresses is not considered further for the purposes assessment.

5.2.5 Other mitigation measures

There is limited scope to reduce EMF beyond the mitigation through design measures identified above. The adoption of any design measure will be confirmed during detailed design.

5.3 Recommended baseline monitoring

As the background geomagnetic field is known, no baseline monitoring is recommended prior to construction. However, post-installation surveys to confirm the cables are laid in the correct location and buried to the correct depth should be undertaken to ensure appropriate mitigation has been implemented and final design is reflective of potential impacts assessed.

6 Potential Residual EMF Impacts on Marine Fauna

The residual EMF impacts of the Proposal on various marine groups are assessed below with references to marine species that are known to occur, likely to occur, or may occur in NT waters and Commonwealth Marine waters proximate to the Proposal's Subsea Cable System. Assessment has been completed for each of the three scenarios described in Section 4. Residual impacts assume that avoidance design measures have been implemented, as described in Section 5. Potential residual impacts have been assessed in accordance with the EIA methodology detailed in Chapter 3 of the Draft EIS.

6.1 Residual EMF impacts of the Proposal on cetaceans

6.1.1 Interference with orientation or navigation of magnetosensitive cetaceans

Residual EMF impacts on cetaceans in shallow coastal and inshore waters

For the Scenario 1 case of the bundled HVDC cable buried to -1m depth at Marker 1 in the Beagle Gulf, the predicted combined magnetic field (i.e., the combined subsea HVDC cable and geomagnetic field) is 62.8 µT at the seabed and 50.6 µT at 1 m above the seabed at the location of the Proposal's HVDC cable (i.e., bundled cable buried to -1 m depth) at Marker 1. The total magnetic field extends from the seabed 'vertically' to between 0 m to 10 m before the background geomagnetic level of 46.16 µT is reached.

For Scenario 2 (i.e., spaced HVDC cable buried to -1 m depth at Marker 1 in the Beagle Gulf), the predicted combined magnetic field is 398.5 µT at the seabed and 226.4 µT at 1 m above the seabed. However, the nearshore water depth at Marker 1 is only 12 m (Notman, 2022); therefore, the combined total magnetic fields at other depths have been estimated as part of this assessment based on the horizontal distance calculated by Norman (2022), given that both the vertical magnetic field and horizontal combined total magnetic fields are perpendicular to the buried spaced HVDC cable.

At vertical heights above the seabed of 2, 3, 5, and 9 m, the estimated combined total magnetic fields are 163.0, 131.4, 100.3 and 76.5 µT, respectively. For those cetaceans swimming at or near the surface (top 4 m water depth), the Proposal's Scenario 2 combined total magnetic fields are between 76.5 and 100.3 µT, which are similar in magnitude as the background geomagnetic field of 46.16 µT. Near the seabed and bottom waters within 5 m water depth at Marker 1, the combined total magnetic fields vary between 226.4 µT at 1 m above the seabed to 100.3 µT at 5 m above the seabed, which are 4.9-fold and 2.2-fold higher than the background geomagnetic field of 46.16 µT.

Any magnetosensitive cetacean passing through the Proposal's narrow band of and relatively weak magnetic fields may sense it as a transient anomaly without interfering in their orientation or navigation abilities using the geomagnetic field. Whilst undertaking local movements or foraging in shallow coastal waters, cetaceans use other sensory modalities rather than magnetoreception that is used predominantly by long-distance oceanic cetaceans. Additional sensory modalities include visual cues (e.g., shallow water terrain, turbidity as a proxy for salinity), acoustic cues (e.g., detecting physical underwater noise gradients, biological sound sources (e.g., coral reef sound scapes, snapping shrimps, sound-producing fish species) and passive listening for prey aggregations, as well as echolocation in the case of toothed whales and dolphins (Torres, 2017). However, olfaction is not a sensory modality that cetaceans can use given the explosive way in which cetaceans breathe, which reduces the usefulness of olfaction (Tyack and Clark, 2000).

Vagrant humpback whales are occasionally present in NT nearshore and offshore waters, namely the Beagle Gulf and the Timor Sea, although these areas are not part of this species core range (DAWE, 2021) they are within the Proposal area. This species is known to use its magnetosensory system to navigate in open oceanic waters. Humpback whales (*Megaptera novaeangliae)* off the east coast of Australia showed an average swimming speed of 2.5 km/hour when singing and an average non-singing swimming speed of 4.0 km/hour during migration and swam at speeds of up to 15.6 km/hour (Noad and Cato, 2007). Therefore, any humpback whale or other large whales passing through the weak magnetic fields of the Proposal's HVDC cables in the water column will do so rapidly with minimum exposure to the cable's disruption of the background geomagnetic field.

Given the transient passage and very short duration of exposure to Proposal-generated magnetic fields, cetaceans swimming through or diving within the water column overlying the buried bundled HVDC cable (Scenario 1) or buried spaced HVDC cable (Scenario 2) in the Beagle Gulf at Marker 1, the Proposal's magnetic field impacts are assessed to have a residual impact rating of ***Minor*** for cetacean orientation, migration, or other movements. The likelihood of occurrence of the Proposal-generated magnetic field impacts on cetaceans is also assessed to be *Unlikely.*

Residual EMF impacts on cetaceans in deeper offshore waters

Under Scenario 3 (unburied spaced HVDC cable), the combined total magnetic fields at the cable surface and 1 m above the seabed are 4,881 μT and 398.9 μT, respectively. Combined total magnetic field intensity at other depths (up to 10 m above the seabed) have been estimated based on using the horizontal distance calculated by Norman (2022), given that both the vertical magnetic field and horizontal combined total magnetic fields are perpendicular to the buried individual HVDC cable. At vertical heights above the seabed of 2, 5, 7, and 10 m, the estimated combined total magnetic field intensities are 228.0, 113.3, 93.4 and 77.2 μT, respectively.

The assessment undertaken indicates that the Proposal's subsea HVDC cable (i.e., spaced cable (unburied) laid on the seabed at Marker 5 in the Timor Sea), reaches background geomagnetic level at 8.41 m (see Table 4-7), so the combined total magnetic field could be expected to be between 10 and 20 m height above the seabed and at an approximate depth of 114 m (Notman, 2022). Based on this it is anticipated that the combined total magnetic field intensities in the midwater and surface waters are predicted to remain at the natural background geomagnetic level of 46.37 μT.

Most migrating whales and oceanic dolphins are air-breathing and are expected to swim within the midwater and near-surface waters when within deeper offshore water within the Proposal area, although some may dive deeper within the water column on occasion.

It is anticipated that those present in the midwater and near-surface waters when passing the Proposal's HVDC cable locations will not be influenced by the HVDC cable's magnetic field. In the case of those cetaceans that may dive deeper within the water column overlying the Proposal's subsea HVDC cable laid directly on the seabed, their exposure to the cable(s) magnetic fields would be transient and short in duration.

Overall, the residual impacts of the Proposal's magnetic fields from its offshore unburied spaced HVDC or bundled cables on the orientation or navigation of oceanic magnetosensory cetaceans are assessed to have a residual impact rating of ***Minor***, with impacts on cetacean orientation and navigation unlikely to occur in migrating cetaceans in offshore Commonwealth Marine waters.

6.1.2 Cetacean live strandings in the vicinity of the Proposal's subsea HVDC cables

It is anticipated that there would be no adverse impacts on cetaceans or increased risk of strandings resulting from the magnetic fields generated by the Proposal's subsea HVDC Cable System. This is based on the findings of independent desktop studies commissioned by the Basslink Project on cetacean live strandings at or in the vicinity of operating subsea HVDC cable system landfalls. The studies concluded that there was no evidence of a causal connection between the cables assessed and active strandings (Warneke, 2001a). This is further supported by review undertaken as a part of this assessment which was not able to find any information of live cetaceans strandings at or in the vicinity of the Basslink cable landfalls during its period of operations (i.e., from the start of operation in 2005 to date).

A residual impact rating of ***Minor*** has been assessed for potential live strandings due to the magnetic fields generated by the Proposal's HVDC cables. This is based on a scale of *Limited* (the cable's magnetic fields reduce rapidly to background geomagnetic field levels within (20 m) and a magnitude of *Negligible.* The likelihood of this impact occurring is also assessed as *Unlikely*, given Australian and overseas experience of cetacean interactions with subsea HVDC cable magnetic fields.

6.1.3 Subsea HVDC cable magnetic fields acting as a barrier to cetacean movements

It is not anticipated that the magnetic fields generated by the Proposal would result in or act as a barrier to cetacean movements. This finding is based on the outcomes of this assessment and literature review which did not find any evidence of magnetic fields generated by subsea HVDC cable acting as a barrier to cetacean movements (see Table 3-2 Gales,2012).

A residual impact rating of ***Minor*** has been assessed for the Proposal's magnetic fields potentially creating a barrier to movements of cetaceans navigating using their geomagnetic sensory system. This is based on a scale of *Limited* (the cable's magnetic fields reduce vertically to background geomagnetic field levels within (20 m) and a magnitude of *Negligible.* The likelihood of this impact occurring is also assessed as *Unlikely*, given the lack of evidence for any magnetic field barrier effects of subsea HVDC cables in the scientific literature reviewed.

6.2 Residual EMF impacts of the Proposal on sea turtles

Residual impacts on sea turtles have been assessed below for nearshore shallow waters of the Beagle Gulf (NT waters) and offshore waters of the Ocean Shoals Marine Park of the Timor Sea (Commonwealth Marine waters).

Residual EMF impacts on sea turtles in shallow nearshore waters

Sea turtles in the shallow NT waters of the Beagle Gulf will be found within the entire water column from resting and/or breathing at the sea surface to the seabed where they feed on seagrass, benthic algae, benthic invertebrates, or fishes. In these nearshore waters, marine turtles will occasionally and transiently pass through the EMF generated in both Scenario 1 and 2.

For Scenario 1 the maximum combined HVDC cable and geomagnetic field of 62.8 µT at the seabed and 50.6 µT at 1 m above the seabed (bundled cable buried to -1 m depth at Marker 1) (see Table 4.5), which are of the same magnitude as the natural background geomagnetic field of 46.16 µT measured at Marker 1 (see Table 4.1).

The maximum combined HVDC cable and geomagnetic field of 398.5 µT at the seabed and 226.4 µT at 1 m above the seabed for Scenario 2 (spaced HVDC cable buried to -1 m depth at Marker 1) (see Table 4.5).

Magnetic fields are important for hatchings when entering the sea for the first time and used to 'calibrate' their orientation and navigation systems. The shoreline of Gunn Point (i.e., cable landfall) is not a well-known nesting beach, with the majority of Gunn Point being unsuitable for nesting due to large intertidal areas with mangroves (Palmer and Smit 2020). Low numbers of turtle tracks were recorded on Gunn Point beach by Chatto and Baker 2008. Based on the unsuitability of this location for nesting, and the limited observed or recorded presence of turtles in the vicinity, it is unlikely that hatchlings would be significantly impacted by magnetic fields when entering sea for the first time at this location.

The literature review indicates that while a localised disturbance of the geomagnetic field caused by a subsea power cable has the potential to alter the course of a migrating sea turtle, it is likely that the maximum response would be some, probably minor, deviation from a direct route to their destination (Normandeau Associates et al., 2011). Based on the transient passage of sea turtles through the Proposal-generated magnetic fields in nearshore waters, any effects or minor deviations are expected to be so small that they are unlikely to be meaningfully measured, detected, or evaluated and are therefore most likely Minor.

Sea turtles feeding on seagrass beds within the cable alignments in Shoal Bay are predicted to continue feeding on the seabed overlying the subsea cables' locations despite the Proposal-generated magnetic fields that are higher than the background geomagnetic field at this location. This can be attributed to the fact that sea turtles are unlikely to be using their geomagnetic sense of orientation or navigation when foraging, as other environmental cues (e.g., olfactory, visual, auditory, and taste) are relied upon for efficient foraging (Tricas and Gill, 2011).

Overall, the Proposal-generated magnetic field impacts on sea turtles for Scenarios 1 and 2 are assessed to have a residual impact rating of ***Minor***. EMF impacts of the Proposal on magnetosensitive sea turtle orientation or navigation are *Unlikely* to occur due the limited extent of the EMF fields and transient passage through the localised cable magnetic fields. No adverse impacts of the Proposal's generated magnetic fields are predicted for EPBC Act listed endangered sea turtles (including the loggerhead turtle (*Caretta caretta*), olive ridley turtle (*Lepidochelys olivacea*), and the leatherback turtle (*Dermochelys coriacea*)) or EPBC Act listed vulnerable sea turtles (including the hawksbill turtle (*Eretmochelys imbricata*), flatback turtle (*Lepidochelys olivacea*) and the green turtle (*Chelonia mydas*)).

Residual EMF impacts on sea turtles in deeper offshore waters

Migrating marine turtles in the offshore Commonwealth Marine waters of the Timor Strait will largely be confined to surface waters due to their requirement for air-breathing and/or resting between dives. Given that the predicted combined magnetic field (i.e., combined subsea HVDC cable plus geomagnetic field) is restricted to bottom waters within 20 m of the seabed, sea turtles swimming at the surface or diving to mid-water depths will only be exposed to Proposal-generated magnetic fields of similar magnitude as the background natural geomagnetic field of 46.37 µT. Under these conditions, residual impacts on sea turtles are assessed to have a residual impact rating of ***Minor*** and the likelihood of occurrence of magnetic field impacts is also assessed as *Unlikely*.

Sea turtles foraging at the seabed may encounter the higher total magnetic fields of greater than 398.9 µT within 1m of the unburied HVDC cables, though exposure is likely to be of short duration due to the need to resurface for air. The transitory passage of forging sea turtles through the Proposal's Scenario 3 offshore subsea HVDC cable's magnetic field near the seabed is most unlikely to affect their perception of the inclination of geomagnetic field that they use for orientation and/or positional mapping. While Notman (2022) did not calculate inclination or declination components of the geomagnetic field or HVDC cable magnetic fields, the HVDC cable's disruption of these two components is limited in the same way as the total magnetic intensity reduces rapidly with distance.

Additionally, these findings are supported by the literature review undertaken as part of this assessment which found no differences between magnetically disrupted and control turtles (no magnets attached) with respect to navigational performance and course straightness (Papi et al., 2000). These findings indicate strongly that magnetic cues are not essential to open-sea migration, orientation, and navigation by sea turtles (Papi et al, 2000).

The residual impact of the Proposal's EMF fields on sea turtles foraging at the seabed or diving through the HVDC cable's higher magnetic field in bottom waters and within about 20 m of the seabed has been assessed to have a residual impact rating of ***Minor***, and the likelihood of occurrence of residual EMF impacts of the Proposal on all the threatened sea turtle species listed in Table 2.1 are also assessed to be *Unlikely*.

6.3 Residual EMF impacts of the Proposal on crocodiles

The literature review of magnetosensitivity in crocodiles (see Table 3.2) indicated that crocodilians may have a magnetosense that they can use for orientation and navigation. The review found that the *lagenar macula* of the inner ear of crocodiles has been hypothesized to allow crocodilians to sense the geomagnetic field for long-distance orientation (Grigg and Kirshner, 2015). However, evidence of magnetosensory perception in crocodiles is weak, with long-distance orientation attributed to other cues that may be used singly or in combination such as visual, celestial, auditory, olfactory, gustatory (taste) and haptic (sense of touch) cues as suggested by Combrink (2014) and Reber (2020).

Overall, a residual impact rating of ***Minor*** has been assessed for the Proposal's subsea cable magnetic fields (i.e., Scenario 1, 2, and 3) potentially interfering with the movements of saltwater crocodiles that may use their hypothesised geomagnetic sensory system for orientation and navigation. The likelihood of this impact occurring is also assessed as *Unlikely*, given the use of other sensory cues used in crocodile movements.

6.4 Residual EMF impacts of the Proposal on sea snakes

The literature review of magnetosensitivity in sea snakes (see Table 3.2) indicated that sea snakes may have a magnetosense that they can use for orientation and navigation, however Crowe-Riddell et al (2019a) concluded that evidence of magnetosensory perception in sea snakes is weak, and long-distance orientation attributed to other cues that may be used singly or in combination such as visual, auditory, and olfactory cues, including dermal phototaxis found in *Aipysurus* sea snakes. The study also found that the absence of electroreceptors and presence of photosensitive cells in the scale organs of *Aipysurus* sea snakes, indicates a lack of magnetic sensory system.

Based on these findings, the residual impacts of the Proposal's subsea HVDC cable magnetic fields on Aipysurus sea snakes are assessed to have a residual impact rating of ***Minor*** for Scenarios 1, 2, and 3. This assessment is based on a scale of *Limited* (the cable's magnetic fields reduce vertically to background geomagnetic field levels within (20 m) and a magnitude of *Negligible.* The likelihood of this impact occurring is also assessed as *Unlikely*, given the lack of evidence for magnetosensing in *Aipysurus* sea snakes, which includes the two critically endangered Leaf-scaled Sea Snake (*Aipysurus foliosquama*) and Short-nosed Sea Snake (*A. apraefrontalis*) that are likely to occur in the Proposal area.

6.5 Residual EMF impacts of the Proposal on bony fishes

Residual impacts of the Proposal's subsea HVDC cable magnetic fields on magnetosensory orientation and navigation of southern hemisphere eels, and potentially acting as a barrier to eel migration have been assessed.

The Indonesian Shortfin Eel (*Anguilla bicolor*) is likely to pass across the AAPowerLink Subsea Cable System in the Beagle Gulf and Timor Sea during breeding migration. As observed in some magnetosensitive species of bony fishes such as the European eel (*Anguilla anguilla*) in the northern hemisphere (Westerberg and Begout-Anras, 2000; Westerberg and Lagenfelt, 2008), the Indonesian Shortfin Eel (*Anguilla bicolor*) is also likely to use the static (DC) geomagnetic field for orientation, homing, and navigation during long-distance migrations.

Consistent with the findings of the literature review and review of studies on northern hemisphere European eels (see Section 3), it is not anticipated that the Proposals HVDC magnetic fields would result in a barrier effect for the Indonesian shortfin eel, and that although short deviations in the trajectories may occur, this would not be considered a significant impact, with the evidence suggesting the eels would continue on their migration path (Westerberg and Begout-Anras, 2000; Westerberg and Lagenfelt, 2008).

Based on the findings of the literature review and the finding that the magnetic fields surrounding subsea HVDC and HVAC cables have little or no effect on eel migration in the northern hemisphere, the residual impacts of the magnetic fields of the Proposal's subsea HVDC cables for Scenarios 1, 2, and 3 are assessed to have a residual impact rating of ***Minor***. The likelihood of occurrence of residual impacts on magnetosensitive eel orientation and navigation is also assessed to be *Unlikely*.

6.6 Residual EMF impacts of the Proposal on elasmobranch fishes

Residual impacts of the Proposal's subsea HVDC cable-generated magnetic fields via induced electric fields are assessed below for elasmobranchs likely to be present in the Beagle Gulf (nearshore NT waters) and the Timor Sea (offshore Commonwealth Marine waters).

During operations, the induced electrical fields around the Proposal's energised HVDC cables are anticipated to mainly interact with benthic or demersal elasmobranch species due to their close association with the seabed and the overlying bottom waters at the cable locations.

In the deeper waters of the Timor Sea (e.g., 114 m deep at Marker 5), pelagic elasmobranchs are not expected to be affected by the very weak induced electric field strengths in the mid-water column up to surface waters, where background natural induced electric fields predominate and to which they are accustomed. In both shallow and deeper waters of the Proposal's subsea HVDC system's alignment, the passage of pelagic sharks through the Proposal-induced electric fields in the water column is expected to be very transient and no impacts are predicted. These pelagic sharks can be expected to momentarily detect the change in the electric field using their electrosense but with no biological consequence or impact.

Residual impacts of induced electric fields on nearshore elasmobranchs

Due to the shallower water within the Beagle Gulf (e.g., 12 m at Marker 1) and considering the worst-case Scenario 2 (i.e., spaced HVDC cable buried at -1 m depth), the induced electric fields at the lower seawater flow of 0.3 m/s are respectively 42.8, 30.9, 25.0, and 19.2 µV/m at 1, 2, 3, and 5 m above the seabed. Similarly at the higher seawater flow of 1.6 m/s, the induced electric fields are predicted to be 228.2, 165.1, 133.6 and 102.2 µV/m at 1, 2, 3, and 5 m above the seabed, respectively.

Based on the literature review (Section 3) undertaken as a part of this assessment, the weight of evidence points to a lack of potential adverse impacts of subsea HVDC cables and induced electric fields on elasmobranchs. The abovementioned predicted induced electric field values are within the range of natural variability in background electric fields in the marine environment (Kalmijn, 1998; Randall et al., 1997). While elasmobranchs are expected to readily detect the Proposal's induced electric fields, including their direction and intensity, their electroreceptors rapidly become insensitive (or desensitise) to an unchanging static DC electric field such as the Proposal's HVDC cable-generated induced electric fields, which are relatively constant during power transmission (except when ramping power transmission up or down, typically as 30 MW steps). Even in the presence of the Proposal's induced electric fields, which are higher than the natural background electric field, elasmobranchs electroreceptors can readily detect a rapid change in the static electric field (e.g., from a prey) as well as oscillating AC electric fields that generated by a prey organism's bioelectric fields.

The residual impacts of induced electric fields generated by seawater flow through the magnetic fields generated by the Proposal's subsea HVDC cables at Marker 1 in the Beagle Gulf on elasmobranch behaviour in nearshore waters for Scenario 1 (buried bundled cable) and Scenario 2 (buried spaced cable) are assessed to have a residual impact rating of ***Minor***. The likelihood of occurrence of residual impacts of induced electric fields on elasmobranchs in nearshore water is also assessed to be *Unlikely*. Therefore, the likelihood of occurrence of residual impacts on each of the listed threatened species of electrosensitive elasmobranchs in Table 2.1 is also assessed as *Unlikely*.

Residual impacts of induced electric fields on offshore elasmobranchs

Deeper water bottom-living elasmobranchs approaching the Proposal's offshore unburied spaced cable at Marker 5 in the Timor Sea (Scenario 3) will detect higher induced electric fields, owing to the cable being laid directly on the seabed.

Section 4.5 (Offshore induced electric fields in the Timor Sea) predicted an induced electric field of 1,537 µV/m at the seabed in the immediate vicinity of the unburied HVDC cable and based on an average seawater flow of 0.5 m/s (SKM, 2002) under Scenario 3. This predicted induced electric field is 106-fold higher than the background induced electric field of 14.5 µV/m. Similarly, the predicted induced electric field at 1 m above the seabed for Scenario 3 is 125.6 µV/m, which is 8.6-fold higher than the background level of 14.5 µV/m. Offshore bottom-living and demersal elasmobranchs are likely to encounter these relatively high induced electric fields as a result of bottom seawater flow (0.5 m/s) through the cable's magnetic field in the vicinity of the Proposal's unburied subsea HVDC cables.

A benthic or demersal elasmobranch approaching the location of the Proposal's spaced HVDC cable on the seabed will span several equipotential lines of the induced electric field and detect a potential difference between its head and its tail, using its widely distributed ampullary electroreceptors. Elasmobranchs sensing this induced electric field within a few metres are expected to potentially exhibit some form of exploratory behaviour (e.g., seeking 'false' prey, or temporary avoidance or attraction behaviour).

Literature reviewed as a part of this assessment concluded that elasmobranchs assessed either appeared to habituate to the artificial EMFs (induced electric fields) or learn that they were not produced by an accessible food source (Orr, 2016), and that with habituation and the lack of a food source, as well as learning, bottom-living elasmobranchs were anticipated to move on to other foraging areas, with no consequential biological impacts (Hutchinson, 2020).

Overall, the residual impacts of induced electric fields of the Proposal's unburied HVDC cables (i.e., Scenario 3) on offshore bottom-living elasmobranchs are assessed to have a residual impact rating of ***Minor***, given the weight of evidence for a general absence of interactions of assessed elasmobranchs with other subsea HVDC cables locations (e.g., Whitehead, 2002).

6.7 Potential Residual EMF impact summary

Table 6.1 presents a summary of the assessment residual impacts of the Proposal's EMF residual impacts on marine fauna.

Table 6.1: Summary of residual Proposal residual EMF impacts on marine fauna

Section	Marine fauna group	Residual impact rating
Section 6.1	Residual EMF impacts of the Proposal on cetaceans	Minor
Section 6.2	Residual EMF impacts of the Proposal on sea turtles	Minor
Section 6.3	Residual EMF impacts of the Proposal on crocodiles	Minor
Section 6.4	Residual EMF impacts of the Proposal on sea snakes	Minor
Section 6.5	Residual EMF impacts of the Proposal on bony fishes	Minor
Section 6.6	Residual EMF impacts of the Proposal on elasmobranch fishes	Minor

6.8 Post-installation validation monitoring

This assessment has not identified any significant impacts of magnetic fields and induced electric fields on marine fauna. Therefore, it is proposed that environmental monitoring programs to confirm these findings are not required. This is supported by the evidence of monitoring results from monitoring undertaken on the Basslink subsea cable interconnector by Sherwood et al. (2016), who concluded that the "*effects of the cable deployment and operation (live cable with an EMF) were minor and transient*".

It is however recommended that a one-off magnetometer survey of the nearshore (Beagle Gulf) and offshore (Timor Sea) Proposal areas be undertaken during early operations to validate and confirm the accuracy of the predicted magnetic fields. A similar survey of marine electric fields in the vicinity of the cables is not required, owing due to the inherent difficulty in measuring such weak electric fields. Induced electric fields can be calculated indirectly from the vertical component of the magnetic field measured by the magnetometer.

7 Conclusions

7.1 Proposal EMF – magnetic field impacts

Based on the findings of the literature review carried out in support of this assessment, the following conclusions are presented for magnetosensitive marine fauna that may be exposed to the magnetic fields generated by the Proposal's energised HVDC cables.

Where an assessment conclusion is found to have a likelihood of occurrence of residual impact to be "unlikely", this does not mean that there is "no effect", since a magnetosensitive species will be able to detect the Proposal's HVDC cable-generated magnetic fields. This may cause short-term or transient effects on individuals of the magnetosensitive species approaching or passing through the HVDC cables' magnetic fields, but the magnitude of impact is considered negligible. The detected effect would need to have consequences at the population or community level to be considered a "significant impact" (Boehlert and Gill, 2010).

The main conclusions for magnetosensitive marine fauna species are:

- Cetaceans:
  - No significant impacts are predicted from Proposal-generated EMFs on magnetosensitive cetaceans.
  - No significant impacts of the Proposal's predicted HVDC cable-generated magnetic fields are anticipated on any EPBC Act listed threatened, listed migratory, or listed marine species of cetaceans in nearshore NT waters of the Beagle Gulf and offshore Commonwealth marine waters.
  - No impacts are predicted on the NT Department of Primary Industry Resources marine protected species of cetaceans.
- Sea turtles:
  - No significant impacts are predicted from Proposal-generated EMFs on magnetosensitive marine turtles.
  - No significant impacts of the Proposal's predicted HVDC cable-generated magnetic fields are anticipated on any EPBC Act listed threatened and migratory marine turtles in in nearshore NT waters of the Beagle Gulf and offshore Commonwealth marine waters.
  - No impacts are predicted on the NT Department of Primary Industry Resources marine protected species of sea turtles.
- Bony fishes (Teleosteii):
  - No significant impacts are predicted from Proposal-generated EMFs on bony fishes due mainly to the general absence of magnetosensitive species. An exception is the Indonesian shortfin eel (Anguilla bicolor), which is magnetosensitive.
  - No significant impacts of the Proposal's predicted HVDC cable-generated magnetic fields are anticipated on Indonesian shortfin eels that migrate across the Proposal's energised HVDC cables.
- Cartilaginous fishes (Elasmobranchii):
  - Elasmobranchs mainly sense magnetic fields indirectly through their electrosensory system and, for which, the impacts are assessed below (Section 7.2).

7.2 EMF – Induced electric field impacts

Based on the findings of the literature review carried out in support of this assessment, the following conclusions are presented for electrosensitive marine fauna that may be exposed to the induced electric fields generated by the Proposal's energised HVDC cables. The principal electrosensitive marine species occurring in the Proposal area are elasmobranchs (sharks, rays and skates).

- Elasmobranchs:
  - No significant impacts are predicted on electrosensitive sharks, skates or rays from the induced electric fields generated by horizontal seawater flows through the vertical component of the magnetic fields surrounding the Proposal's energised HVDC cables.
  - Given that the induced electric field is a continuous, static electric field of the same nature as the background electric field, no significant impacts on elasmobranch are expected given the small area of seabed or small volume of bottom waters affected.
  - No significant induced electric field impacts on EPBC Act listed threatened, migratory or listed marine sharks, skates or rays.

7.3 General conclusion

While magnetosensitive marine species will be able to detect the magnetic fields generated by the Proposal's energised HVDC cables, this assessment has concluded that EMF effects in most cases are unlikely to occur due to the weak static DC magnetic fields (measured in microTesla), which are of similar magnitude as the natural background static DC geomagnetic field.

A high level of confidence can be placed on the findings of the present report based on experience gained at other HVDC subsea cable projects and operations, including Basslink (Australia's other subsea HVDC cable system) and other field studies:

- Basslink HVDC subsea cable:
  - Sherwood et al. (2016) undertook a review of cable installation and operational effects of the Basslink subsea cable and overseas subsea cable studies and concluded that the marine biological effects of cable installation are transient and relatively minor where the cable is buried on soft sediment seabed.
  - The independent Bass Strait Environment Review Committee (BSERC), chaired by Professor John Sherwood of Deakin University, was established to oversee the monitoring of the environmental effects during the installation and operation of the Basslink operation and confirmed that the magnetic fields and induced electrical fields generated by the Basslink HVDC cable were within the range of predicted values and that the ecological impacts were minimal (as reported in Sherwood et al., 2016).
- Transpower HVDC subsea cable, Cook Strait, New Zealand:
  - Whitehead (2001) concluded that the presence of the Transpower cable system does not appear to affect the commercial shark fisheries or federally protected shark nurseries along the North and South Island. The results of this study concluded that the operational multi-cable system does not disturb the general ecology and behaviour of sharks and rays in the waters immediately surrounding the system.

7.4 Uncertainty

Uncertainty regarding the behavioural responses of magnetosensitive and/or electrosensitive species not studied and different settings, as is the case in Northern Territory, necessitates consideration of means to minimise EMF from the subsea cables. Avoidance and mitigation measures through design to reduce EMF strength from subsea cables have been identified in Section 5 and will be confirmed during detailed design, these include:

- Cable configuration. By placing the cables closer together, preferably bundled, there is a greater mutual cancellation of EMFs. Closer cables also increase the rate at which the magnetic field diminishes with distance from the cables.
- Burial depth. Cables buried at least 1 m for protection against anchor hook-ups or bottom trawled fishing gears coincidently reduce magnetic fields at the seabed and reduce the strength of induced electric fields. Lower strength electric and magnetic fields at the seabed are less likely to be detected by marine fauna or affect their behaviour.

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8.2 Personal Communications

Saijie Sim. 2023. Email from Seiji Sim, HVDC Submarine Cable Project Manager, Sun Cable Singapore to David Balloch, Director EnviroGulf Consulting. Dated 29 June 2023.

Appendix 1 – The ICPC (2021) Environment Update

Prepared by Dr. Mike Clare
Marine Environmental Advisor
International Cable Protection Committee.

December 2021.

THE ICPC
ENVIRONMENT UPDATE

By Marine Environmental Advisor, Dr Mike Clare *Issue 220 • December 2021*

Headlines:

Overview of current state of knowledge concerning submarine cables and the marine environment

New studies provide updated state of knowledge since OSPAR Best Environmental Practices in Cable Installation and Operation was published in 2012

Long-term field studies reveal only minor environmental impacts of submarine cables

FOREWORD:

The ICPC is committed to understanding the marine environment and its interactions with cables, surveys, and installation. Furthermore, the ICPC has devoted considerable effort to understanding how the submarine cable industry may reduce any impacts and help in achieving its current and future strategic goals to monitor, advise and take appropriate action. In line with these objectives, the ICPC has been working with the European Subsea Cables Association (ESCA) to determine the current state of scientific knowledge regarding the impacts of cables in the marine environment. This has been particularly motivated by ongoing discussions with the Environmental Impacts of Human Activities (EIHA) Committee of the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic. ICPC and ESCA are collaborating to assist OSPAR in bringing the technical and environmental understanding of submarine cables up-to-date, based on the latest evidence and technology; particularly those developed since the OSPAR *'Guidelines on Best Environmental Practices in Cable Installation and Operation,'* which was published in 2012. As part of this review, the ICPC's Marine Environmental Advisor has synthesised the available peer-reviewed literature to provide an up-to-date view of how submarine cables interact with the marine environment. This *Environment Update* provides an overview of that review, in-order to provide ICPC Members with-ready access to the current evidence base.

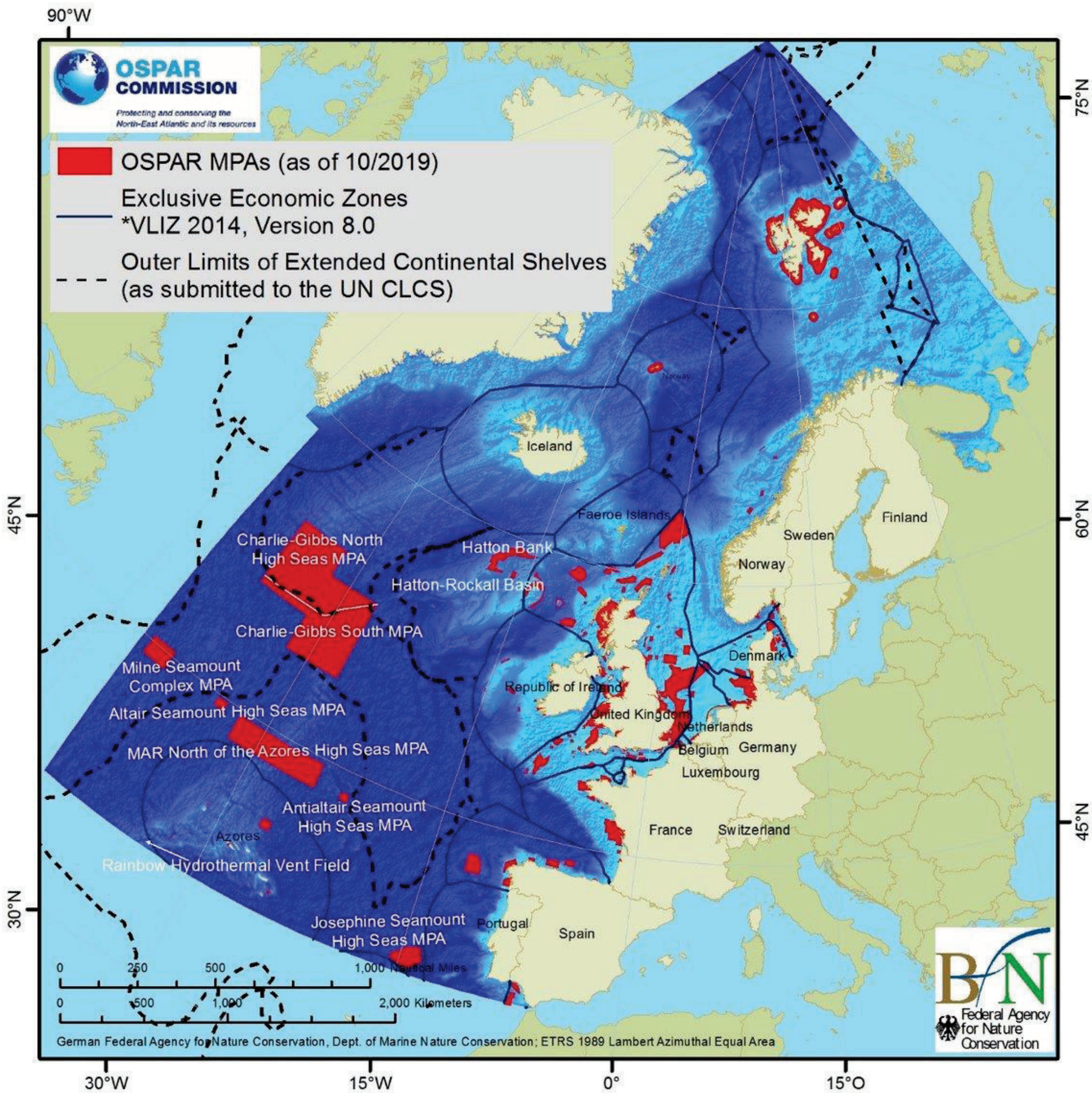
INTERACTIONS BETWEEN SUBMARINE CABLES AND THE MARINE ENVIRONMENT

Overview

This update is intended to highlight recent studies that have been published since the OSPAR 'Guidelines on Best Environmental Practices in Cable Installation and Operation', and hence also since 2009's UN World Conservation Monitoring Centre and ICPC co-authored report 'Submarine cables and the oceans: Connecting the World' (Carter et al., 2009). These new studies include field studies, which were largely absent from those prior reports, and focus is placed heavily on studies published in peer-reviewed scientific journals. The UN WCMC-ICPC report continues to be a very useful reference; however, ICPC efforts are also currently focused on providing an updated version of that report, which is now more than 12 years old. Also important to note is the

UN WCMC-ICPC report focused on telecommunications cables, and did not address environmental impacts of power cables. A particularly relevant review was published recently that provides a good overview on power cables and their environmental effects; concluding that 'Overall impacts on ecosystems are considered minor or short-term' and outlines areas where additional data / knowledge should be acquired, primarily focusing on electromagnetic effects (Taormina et al., 2018).

▼ **Fig. 1: The OSPAR region and the network of Marine Protected Areas (MPAs) from [https://oap.ospar.org/.](https://oap.ospar.org/)**



Ongoing relevant work by ESCA

This literature review complements an ongoing technical review of cable installation and operation activities led by the European Subsea Cables Association (ESCA). The ESCA review will make a clear distinction between different types of submarine cables and thus to provide greater clarity than currently exists in the OSPAR *Best Environmental Practices.* This clarification will explain how different types of cable each serve different purposes (e.g. transferring power, communications or servicing hybrid purposes), have different material properties, require differing degrees and types of burial and/or protection, and therefore will have distinctly different interactions with the marine environment. A good example of this is unpowered telecommunications cables that have no discernable electromagnetic field, in contrast to power cables. The types of cables that will be defined in the ESCA technical review will include:

1. Telecommunications cables, including legacy coaxial cables, and modern fibre-optic cables.
2. Power transmission cables, further differentiating between: long-distance interconnectors and export power cables; short-distance power cables (i.e. domestic links); and power cables for offshore renewables developments.
3. Other types of cables such as military cables, hybrid scientific cables (e.g. that transmit both power and comm-unications), and oil and gas cables.

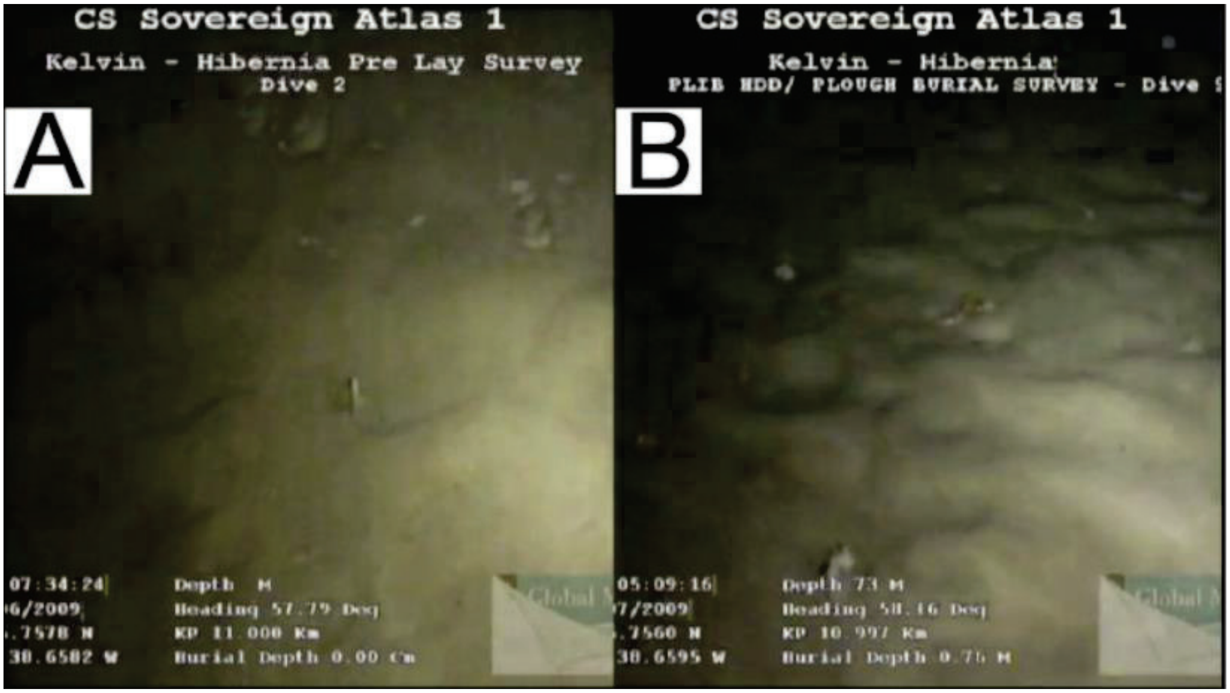
A REVIEW OF THE CURRENT STATE OF KNOWLEDGE CONCERNING THE ENVIRONMENTAL IMPACTS OF SUBMARINE CABLES

The following literature review mirrors the headings in the OSPAR 'Guidelines on *Best Environmental Practices in Cable Installation and Operation*' (BEP), under the section '*Potential environmental impacts associated with submarine cables,'* and provides details on specific issues pertaining to submarine cables and highlights relevant literature identified in the review.

Disturbance by the placement of cables / seafloor recovery

Cable laying is a one-off event, but there can be a need for occasional maintenance or repair works. The extent and significance of any effects associated with cable laying, operation and removal will be dependent on a range of factors, e.g. site characteristics (physical and ecological), cable type; cable laying methodology; cable diameter and length etc. Cables may be surface laid (most common for telecommunications cables, particularly those in deep water), buried (e.g. requiring ploughing, jetting or trenching), or protected (e.g. by rock placement).

Several repeat surveys (primarily photographic) have been performed since the issue of the OSPAR BEP guidelines to document the pre- and post-installation



▲ **Fig. 2: The Kelvin-Hibernia cable route at 73 m water depth prior to cable burial (A) and two weeks after burial (B). All traces of disturbance were removed by the strong tidal regime. From Kraus and Carter (2018). Original image source: Alasdair Wilkie, Hibernia Networks.**

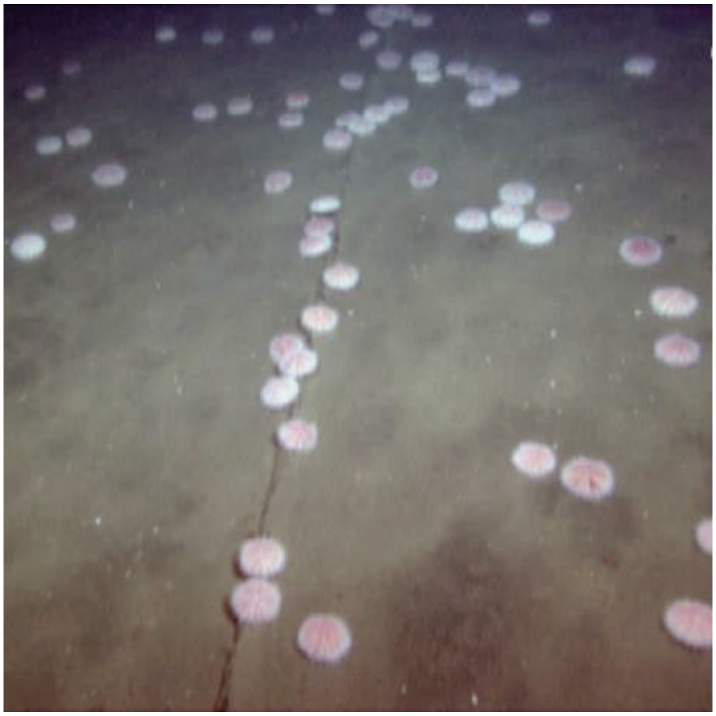
condition of the seafloor following the installation of buried cables that provide new insights into the impacts of these different activities. Time-series observations of surface laid and buried submarine telecom-munications and power cables show that the seabed typically returns back to its natural state within months to years - the rate of recovery depending upon (i) the mode of cable deployment, (ii) wave and current regimes, (iii) rates of sediment supply to the ocean, (iv) seabed topography and geology and (v) biological activity. The continental shelf, where most cable repairs take place, is subject to waves, ocean currents and tides that typically restore the seabed back to its normal state on timescales of days (for strong tidal regions) to years. Relevant studies that cover this area include:

Surface-laid telecom cables in deep-water (Carter et al., 2020): Once in depths below the photic zone (~200m in clear ocean water) encrusting epifauna appears to decline. Studies of recovered sections of cables from the central Pacific, North Atlantic and Mediterranean Sea that had lain on the seafloor between 38 and 44 years found that the cables were well-preserved and physically intact. The cables had clean outer sheaths with no trace of biological encrustation (note that cables are not coated with antifouling agents).

Surface laid and buried telecom cables (Kraus and Carter, 2018): 'Surveys also suggest that benthic communities recover at rates similar to physical restoration. With few exceptions, the physical presence of a cable and the disturbance caused by its burial have little effect on the benthos studied.' (NB: this study relates to jetted and trenched cables). This study focused on a number of submarine cables (including buried and surface laid examples) on the continental shelf, and found that benthic recovery (i.e. to pre-lay state) is very site-dependent, and can occur between weeks to one year at 0-30 metres water depth and within seven years beyond 130 m water depth (after burial). Physical recovery varies with sediment supply, wave/current action and burial mode. For instance, frequently shifting coastal sands are least susceptible because the associated fauna are resilient and opportunistic - attributes that allow them to re-establish fairly quickly. With regards to installation effects, the small size of telecommunications cables and their controlled deployment on the seabed surface are unlikely to form a significant plume. If a plume forms it is unlikely to have a lasting effect on the benthos as evinced by studies of power and telecommunications cables that reveal little or no change in the benthic fauna before and after a cable deployment (e.g. also see the following studies by Kuhnz et al., 2015; Kogan et al., 2006).

Surface laid hybrid (powered communications) cable (Kuhnz et al., 2015): 'the major conclusion of the study is that the MARS cable has had little detectable impact on seabed geomorphology, sediment conditions, or biological assemblages.' Some surface-laid cables self-buried following installation, but some sections remained exposed to provide substrates for endemic faunal elements. New analysis of a more recent 2020 survey (i.e. 13 years after the cable was installed) concluded that **'the MARS cable has had little detectable impact on seabed geomorphology, sediment qualities, or biological assemblages.'** (Kuhnz et al., 2020).

Surface laid hybrid (powered communications) cable (Kogan et al., 2006): Following eight years of the ATOC coaxial communications cable, 'results indicate that the biological impacts of the cable are minor at most.' However, there were some megafaunal differences related to sea anemones colonised on exposed sections of the cable and some fish gathered around the cable. These findings are also supplemented by a study by Kogan et al. (2003).



◀ **Fig. 3: Sea urchins moving across the MARS cable offshore California, from Kuhnz et al. (2020).**

Buried power cables and with seabed protection (Sherwood et al., 2016): 'At over half the sites studied the trenched cable was not visible after one year,' 'the ecological effects of the cable installation on epibiota have been transient and minor for soft sediments where the cable is buried.' 'Within three years the protective cable shell fhad a benthic community like that on surrounding areas. 'It should be noted that the epibiota in deep reaches of the cable route were insufficient to make statistically viable comparisons. This study focused on the Basslink HVDC cable, which was laid on the seafloor in shallow water due to outcropping bedrock which inhibited burial, so a protective metal shell was laid over some sections of cable to protect it. This study therefore provides an interesting comparison between laying in soft substrate and also on hard substrate where protection needed to be installed. Where epifaunal colonisation was noted (growing on the cable and fragments of consolidated sediment exposed in the trench), this disappeared as the trench infilled with natural sediment and the seabed returned to its normal state – a process that took one to two years.

Buried power cable (Andrulewicz et al., 2003): A study of the environmental effects of the installation and functioning of the submarine SwePol Link HVDC transmission line in the Baltic Sea concluded: 'No significant changes in zoobenthos species composition, abundance or biomass which could have been clearly related to cable installation.'

(See Table 1 on the folllowing page).

Site summaries and recovery times for case studies as referenced by superscripts. Note recovery times are determined by the time of survey not by events such as storms that may alter any effects of burial. Also note that recovery times are specific to the study areas, e.g., recovery of seagrass varies with the species with *Zostera marina* recovering faster than *Posidonia oceanica*. [1.] Linders et al. (2003); [2.] Austin et al. (2004); [3.] Birklund (2005); [4.] Sherwood et al. (2016); [5.] Andrulewicz et al. (2003); [6.] Global Marine Systems Ltd (2015); [7.] Kuhnz et al. (2015); [8.] Grannis (2005); [9.] NOAA (2005). CSUS = continental shelf and upper slope.

CSUS Zone Water Depth (WD) in metres	Cable C= communication P=Power	Burial	Sediments	Recovery
Shore/intertidal	Norderney C[1]	Vibrating plough	Salt marsh	Some sites 2yr, others 5 to 7yr.
	Puget Sound C[2]	Trench	Seagrass meadows - *Zostera marina*	4 to 6yr.
Inner continental shelf **~0-30m WD**	Nysted P[3]	Barge-mounted backhoe	Modern cover is mud to coarse sand overlaying glacial mud	Recovery began within 1yr.
	Basslink PC[4]	Trench	Sand on Victorian side	1yr
		Pipe protection	Basaltic rocky reef on Tasmanian side	Pipe encrusted by local biota within 3.5yr.
	SwePol P[5]	Trench	Sand	≤1yr
	Sthn Cross C[6]	Plough	Sand + shells	Plough furrow remained filled for 15yr but fill thinned locally by up to 0.7m.

▲ **Table 1: Summary from Kraus and Carter (2018) outlining the recovery times for the different sites studied, including reference to the burial tool.**

Specific commentary on burial and comparison of techniques

The OSPAR BEP stated '*As far as the burial technique is concerned, installation via jetting by means of sledge or ROV or use of a plough involves the lowest environmental impacts*.' This comment still stands as valid. More recent studies provide some further insights into the relative impacts of jetting and ploughing. While the physical footprint of seafloor disturbance is generally greater for ploughing, jetting may create wider reaching impacts than ploughing. Ploughing generally creates a larger area of direct seabed disturbance (while the area excavated is typically <1 m wide, the disturbance zone can reach 2-8 m width) compared to that affected by jetting (typically <1 m wide) (Muneez et al., 2018). However, the nature of disturbance, as well as the physical footprint of the activity should also be considered when assessing the environmental impacts.

Jetting suspends sediment that may escape from the trench, leaving it partially filled, and sediment ejected from the trench may settle on the margins to form berms (typically within 100 m of the trench), while suspended clay and silt may disperse up to 2 km away (Kraus and Carter, 2018). Therefore, compared to ploughing, the effects of jetting can often be more widely felt (BERR, 2008). Turbidity can persist for several days depending on the duration of the whole cable-laying process. At the Nysted offshore wind farm (Denmark), it took one month to excavate 17,000 m^3 of sediment for a 10.3-km long, 1.3-m wide and 1.3-m deep cable trench. However, at any given location on a cable route, disturbance will typically persist from a few hours to a few days (Taormina et al., 2018).

Local to regional environmental (substrate, wave/current etc.) conditions play a key role in rate of seafloor recovery. As highlighted already, Kraus and Carter (2018) performed a particularly relevant study that documented the seabed recovery after cable burial based on analysis of repeated seafloor surveys, which included comparison of sites where ploughing and jetting were used. This study made the important conclusion that the environmental setting and natural processes are the dominant controls on how fast the seafloor will recover:

- Seafloor recovery will be fastest in areas of high sediment supply, and where energetic waves or currents redistribute sediment (for instance the inner to middle continental shelf – 0-80 m water depth). Recovery can occur within weeks to less than two years.
- Sediment supply and wave/current activity generally (but not always) decreases offshore, hence recovering is typically longer in deeper waters.
- On the upper continental slope (130-2000 m water depth), trenches infilled after about eight years, where sediment supply is high but more than 15 years where sediment supply was low.
- Benthic communities were found to recover at rates similar to physical restoration and with few exceptions, the physical presence of a cable and disturbance associated with its burial had little effect on the benthos.

Kraus and Carter (2018) found that seafloor recovery takes longer after jetting than ploughing. Water-jetted trenching was found to be more disturbing than ploughing and took more than five years for recovery, while recovery from jetting in similar water depths took less than two years. These conclusions are in line with and add to the previous statements the OSPAR BEP, which states that ploughing is generally less environmentally impactful than jetting. Both jetting and ploughing are considered to have a relatively short-lived environmental impact. The consensus of these prior studies is that jetting has a relatively higher environmental impact than ploughing (despite the bigger physical footprint of ploughing). When considering which technique to use, it is important to assess the local hydrodynamic and benthic conditions to determine which impacts are anticipated and how sensitive the local benthic communities are to those impacts.

Noise

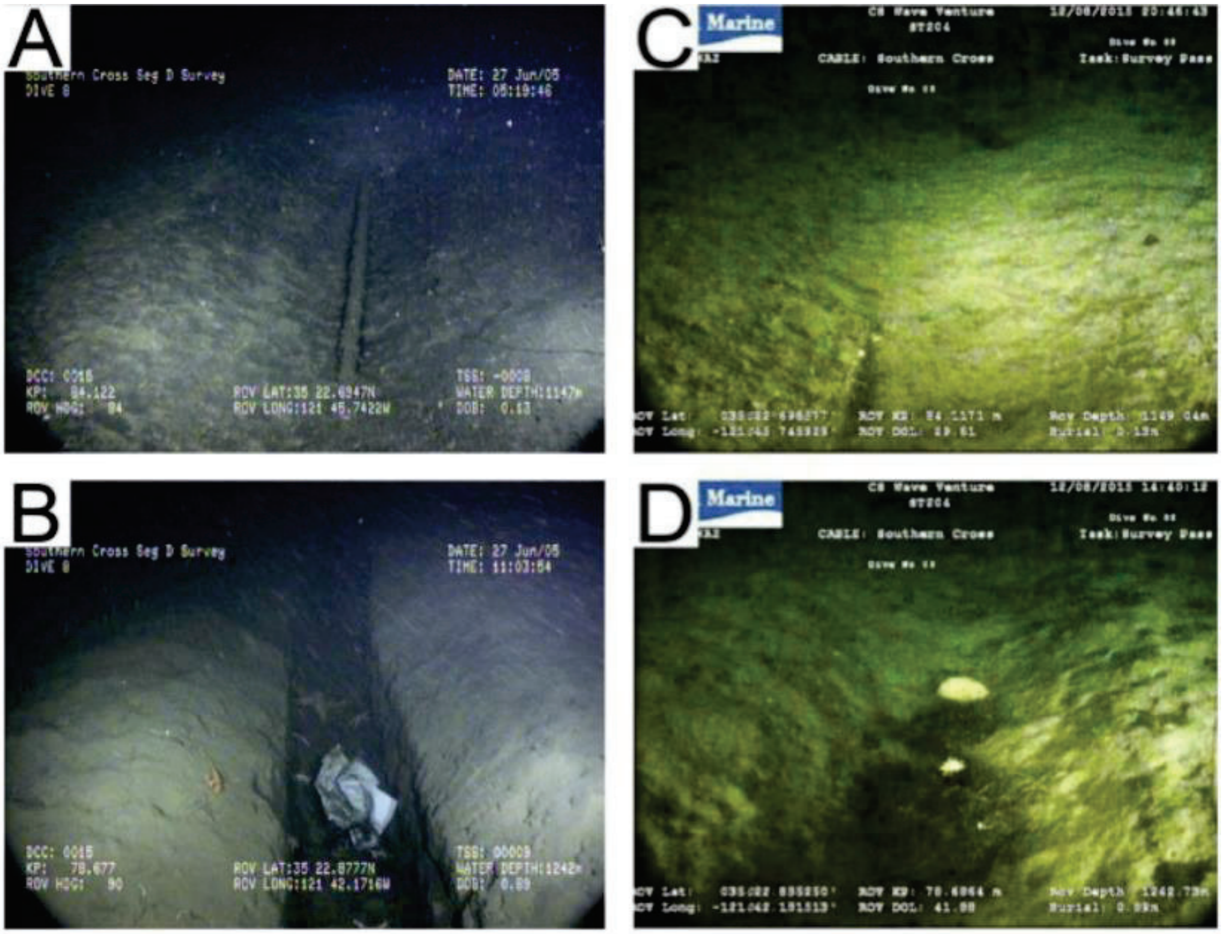
Hale (2018) reviewed noise associated with cable installation and its potential effect on marine organisms. He noted that in contrast to '*chronic anthropogenic sound*' in the ocean caused by dredging, fishing, shipping, large-scale seismic surveys and other noisy activities, cable deployment is a one-off operation. Noise is generated during cable route surveys, but this typically involves high frequency sonar systems that have a low effect on noise sensitive organisms compared to prolonged, mid-to-low frequency acoustic systems favoured by the hydrocarbon industry and military (e.g. Kates Varghese et al., 2020). With surface cable laying, sound generation will be restricted to that of the cable ship. Noise from cable burial is considered to be comparable to a small dredging operation, but it is a one-off operation.

Heat emission of power cables

A relevant study by Müller et al., (2016) provides a comparison of field measurements and numerical modelling, which represents a significant addition since the BEP, which highlighted a paucity of field measurements. This study shows that seasonal heating and cooling of sea water and the thermal properties of marine sediments are dominant factors affecting heat in sediments. Heat from buried submarine power cables is a second order source. Thus natural variability dominates and challenges the value of the '2K' criterion as a threshold for anthropogenic heating from cables. While the (Müller et al. 2016) study involved modeling, some confidence can be placed in the simulations because the model is underpinned by field measurements of the thermal properties of subsea sediments. There is still a knowledge gap regarding the effect of heat on marine organisms (Meisner et al, 2006; Taormina et al., 2018). One approach to this problem is to compare the biota at cable sites and at cable-free control sites. This is based on the premise that if there is a heat effect, there should be some difference in the biota compared to the control sites (i.e. not found by Sherwood et al., 2016; Kogan et al., 2006; Andrulewicz et al., 2003).

Specific commentary on telecommunications cables: In the case of telecommunications cables that are powered, the power load is a constant direct current of about 0.6 to 1.0 amperes. This compares to the ~2 to 2.5 amperes drawn by a mid-range, laptop computer. Thus, heat generation is small and becomes negligible in the presence of heat-dissipating seawater or sediment pore waters. By their very purpose, subsea power cables carry large amounts of power the absolute amounts of which depends upon power cable type.

In a review of environemntal impacts of submarine cables, Meißner et al. (2006) concluded: that 'Transmission capacity of power cables powering repeaters of telecommunication cables is comparably low and heat emission by them is supposedly negligible.'



▲ **Fig. 4: Southern Cross Segment D on the upper continental slope showing a broad jetted trench typical of soft sediments at 1149 m WD in 2005 (A) and in 2015 (C). Steep-sided trench formed in consolidated sediments with paper debris at 1242 m WD in 2005 (B) and in 2015 (D) when the trench had partly filled with sediment from the surrounding seabed and localised collapse of trench walls; from Kraus and Carter (2018). Source: Dean Veverka, Southern Cross Cable Network.**

Electromagnetic fields

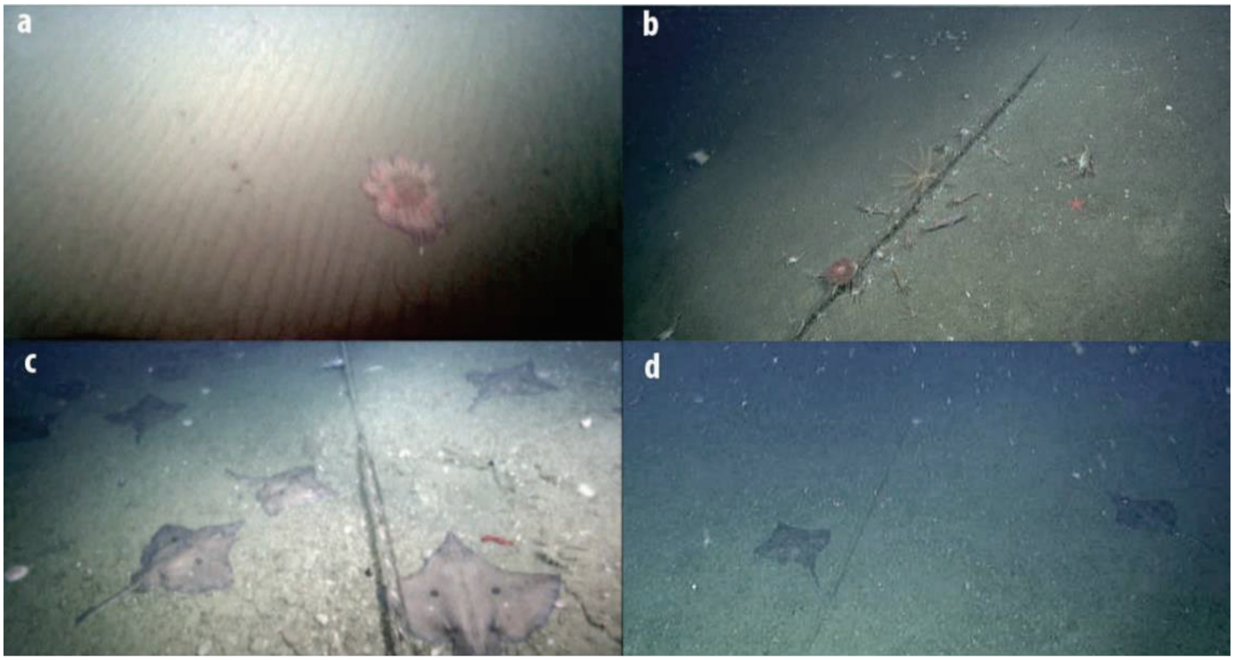
Electromagnetic fields generated by power cables

Direct observations of magnetic fields generated by power cables show fields are tightly constrained to the cable (Sherwood et al., 2016). Those observations support model-based predictions thereby providing confidence in the model simulations (Normandeau et al., 2011). In the case of the Basslink cable (Sherwood et al., 2016), direct measurement of the total magnetic field associated with the operating cable showed a variation of <1% of the natural field at 5 m above the cable. These observations were within 0.8% of calculated values. For the SwePol cable in the Baltic Sea, magnetic fields were significantly close to the cable but did not exceed natural variability at a distance of 20 m (Andrulewicz et al., 2003), while Love et al. (2017c) found no variation from background levels at a distance of 1 m from power cables offshore California, USA. Calculated predictive data for various cables suggest magnetic fields drop to natural levels within ~10m of a power cable (Normandeau et al., 2011). Thus, where cable-related fields exceed natural levels, they are tightly constrained about the cable, i.e. within 5-20m depending upon several variables. These variables are discussed in the following section, which addresses the effect of EMFs on marine organisms (EMF = electro-magnetic fields - a broad term to cover the various fields about a cable).

Until recently, knowledge of EMFs on sensitive marine biota was limited. This situation partly reflected a dearth of real-world field studies. Uncertainty was compounded by complexities associated with the different responses of various marine organisms to EMFs that themselves varied as a function of (i) cable voltage, (ii) AC or DC systems, (iii) depth of cable burial, (iv) cable orientation and other factors. However, at least three major reviews (Normandeau et al., 2011; Copping et al., 2016; Albert et al., 2020) and several field studies (Sherwood et al., 2016; Kuhnz et al., 2015; Andrulewicz et al., 2003) have been completed that provide a more informed perspective. The common finding of this research is that there is a lack of evidence for positive or negative effects of cable EMFs on the species studied.

Power cables that connect oil and gas platforms (Love et al. 2016): Of the various animal communities studied along power cables installed in the Pacific OCS Region, none exhibited a significant biological difference for different survey zones. However, plants in a nearshore zone varied with habitats, which the authors concluded to be a function of water depth and the physical presence of a pipeline and cables, rather than an effect of EMFs. Of the few observed electro-sensitive species, there was no conclusive evidence that those species were attracted or repelled by EMFs. In addition, the studies showed EMFs were relatively stable over the observational period and were tightly constrained to the cables.

AC inter-array and export power cables (Love et al., 2017a): Adajacent to power cables offshore southern California and in Puget Sound, USA, baited traps were placed near a power cable to assess whether Dungeness crab preferentially avoided cables or crossed them. They found no evidence that the EMF emitted by energised submarine power cables influenced the crab and observed no differences in the crab responses whether the cables were buried or not. Further data was published from the southern California cables, that made field EMF measurements and of fish and invertebrate communities, finding no evidence that fishes of invertebrates were preferentially attracted to, nor repelled by, the EMF emitted by the cables. In a follow-up



▲ **Fig. 5: Megafauna along the MARS cable route, offshore California, showing sand ripples and a sea star where the cable is buried and no habitat is disturbed (a), cable at 226 m depth with an attached anemone and crinoid (b), skate aggregation at 303 m water depth in early 2008 near the unenergised cable (c), and fewer skates in the same area.**

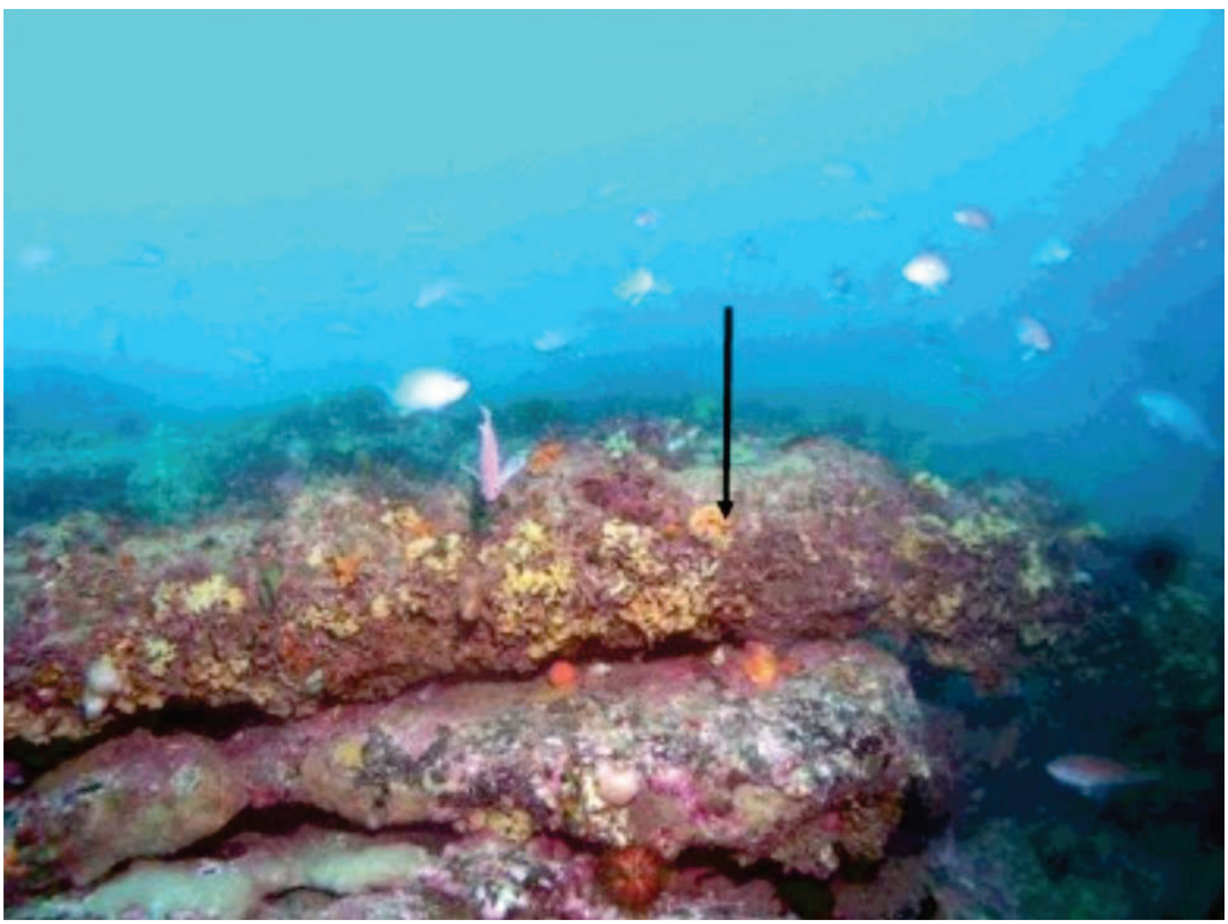
study by Love et al. (2017b), any differences in fish or invertebrate densities were related to differences in physical characteristics of the seafloor habitats, and not the EMF. Macrophytes did not appear to respond to the MF from the cables either. Instead, the study concluded that differences in plant communities were likely attribuatble to water depth and habitat type. Another study of the same power cables offshore California, USA found that EMFs decline to background levels within c.1 m of the cable. A third study by Love et al. (2017c) found that total fish densities were higher around the cables than over the natural habitat, however no statistical difference in species composition (fish and invertebrates) between assemblages along energised and unenergised power cables.

DC power cable: Chinook salmon smolts were tracked using acoustic biotelemetry to examine their migration through San Francisco Bay before and after the installation of an 85 km high-voltage DC transmission cable by Wyman et al. (2018). Cable energisation did not significantly impact the proportion of fish that successfully migrated nor the probability of successful migration. Cable influence appears to have been spatially variable. However, after cable energisation, higher proportions of fish crossed the cable, which resulted in a more southerly distribution of fish compared to their normal route, but other environmental factors were also suspected to play an important role.

Surface-laid hybrid cable (Kuhnz et al., 2015): For the MARS hybrid cable offshore California, USA local variation in benthic megafaunal communities near the cable (within 50 –100 m) was deemed to be minor or undetectable. With regard to the EMF-sensitive skate, *Raja rhina*, there was no significant difference in the abundance of skates near the live cable compared to 50 m away **after the cable was energised in 2010 (d). Photographs from Kuhnz et al. (2020).**

Buried power cables and with seabed protection (Sherwood et al., 2016): The Basslink study noted that the effects of the cable deployment and operation (live cable with an EMF) were minor and transient. This may be applicable to the section of the cable laid across a rocky reef. There, the cable was protected by an iron conduit, which over 3.5 years became encrusted with a rich epibiota

▼ **Fig. 6: Video still image of the half protective shell (arrowed) over the Basslink cable offshore Australia and its surrounding reef in April 2009; from Sherwood et al. (2016). Photo: CEE Consultants.**



similar to that on the reef. However, it is unclear if the iron conduit affected the cable EMF. The induced electric field, i.e. formed where seawater flows through a magnetic field, was directly observed for the Basslink cable. The field was found to be difficult to measure due to widely fluctuating values - a condition attributed to turbulence and other rapid changes in marine current speeds over the cable. However, given that the strength of the electric field is directly proportional to that of the magnetic field, then the induced electric field will be <1% of its natural counterpart for a given current speed.

Experimental (laboratory) surface laid power cable (Jakubowska et al., 2021): The aim of this study was to determine the effect of static magnetic fields (10 mT) and electromagnetic fields (50 Hz, 1 mT) on the behaviour (attraction to or avoidance of magnetic fields) of early life stages of O. mykiss. The study investigated whether there were differences in behaviour between larvae reared under natural GMF conditions and those previously exposed to SMF or EMF for 40 days. None of the groups of larvae avoided either the static or alternating field. In addition, no stress response (i.e. a change in the oxygen consumption rate) was recorded for O. mykiss larvae exposed to magnetic fields. These results suggest, for the first time, that early life stages of rainbow trout can detect and are attracted to artificial magnetic fields of a magnitude recorded in the vicinity of submarine cables, with no visible signs of stress (i.e. increased oxygen consumption).

EMFs from power cables including field measurements and numerical modelling (Hutchison et al., 2020): The EMF associated with two subsea, buried, high voltage direct current (HVDC) cables was determined using custom-built instrum-ntation to simultaneously measure the magnetic and electric field. The in situ measurements were taken at the Cross Sound Cable (CSC), which runs between Connecticut and Long Island and at the Neptune Cable that connects New Jersey and Long Island, USA. The study then assessed the behavioural response of two bottom-dwelling marine animals, to the EMF environment created by a HVDC cable. Anthropogenic emissions of electromagnetic fields (EMFs) from subsea electricity transmission cables were measured at a magnitude similar to the background geomagnetic field. An ecologically significant behavioural response to the EMF of the Cross Sound Cable was observed in the electro-sensitive Little skate, Leucoraja erinacea and the presumed magneto-sensitive American lobster, Homarus americanus. Both skates and lobsters were able to move through the EMF emitted from a HVDC cable; however, the changes in behavioural movements may infer ecological consequences for electro- and magneto-sensitive species. The total zone affected by cable induced magnetic fields (DC and AC) in this study, was 5–10 m on either side of the cable, inferring the potential area of influence to be 10–20 m wide. The fields also extend vertically (e.g. 2.5 m), however decrease in magnitude with distance from the cable. The measured AC electric field extended approximately 100 m and may represent a larger area of potential influence for electro-sensitive species. Furthermore, the DC magnetic field was scalable to the power in the cable indicating that future higher capacity cables may produce higher magnitude distortions of the geomagnetic field.

An ongoing research project that is also relevant is the ElasmoPower project led by Wageningen University that aims to quantify the impacts of renewables power cables on sharks and rays; however, at the time of writing peer-reviewed outputs were not available.

Two other non-peer-reviewed reports provide useful information (also synthesising some of the above studies) presenting the results of a desk study and pilot field study in the Dutch North Sea: study one and study two. A desk study identified that potential effects of subsea cables were scarce), which led to the development of a field pilot study that made real time EMF measurements adjacent to offshore wind power AC cables in combination with video recordings. Measured EMF values were found to be relatively low (albeit measurements were made during periods of low wind and hence low relative power transmission) and comparable with other measurements made at offshore wind farm export cables in Belgium. A difference in density of at least two species groups was observed above the cable, compared to areas further away; however, this is based on a single observation and no repeated quantitative analysis could be conducted and the study suggests for firm conclusions can be drawn. The study instead demonstrated the feasibility of conducting synchronous field-based EMF measurements and acquisition of video footage for future quantitative assessments. These studies also include their own literature review that may be of interest to ICPC Members.

Specific commentary on electromagnetic fields generated by telecom cables

The difference in EMFs between power transmission and telecommunication cables is supported by several independent studies including the OSPAR Commission's Cable Guidelines which state: *'Electromagnetic fields are generated by operational power cables. This effect is much more relevant to power transmission cables than to telecommunications cables, even though modern fibre-optic cables are equipped with electrical power supplies (OSPAR 2009). Although there are specific studies according to which coaxial telecommunication cables also induce electric current in the surrounding area, such current is very low. These aspects are therefore not examined in further detail here.'*

A review by Albert et al. (2020) that focused on EMF effects of cables similarly concluded: 'Although telecommunication (i.e., fibre optical) cables cover a large area of the seabed, their electric and magnetic emissions are substantially smaller than those of SPCs (Carter et al., 2009; Meißner et al., 2006;

Tricas and Gill, 2011). The total voltage required for a typical 7500 km transatlantic telecommunication cable, equipped with 100 repeaters maintaining the optical signal, is around 10 kV (no magnetic field measurements found) (Meiβner et al., 2006).'

A recent study that includes an estimate of the global footprint of telecommunication cables on the seafloor *incorrectly* assumed the same electromagnetic field of power transmission cables for telecommunication cables (Bugnot et al., 2021). It is therefore important to clarify that telecommunication cables are very different to power transmission cables for a number of reasons (as listed below) and produce an even smaller electromagnetic field.

- Many telecom cable systems have no live current at all ('unrepeatered systems') (generally cable routes or sections of telecom cable under c.300 km in length) and are unpowered and hence have no or negligible electromagnetic field. This length also varies as new technology allows longer unrepeatered sections; hence the future effects will be much smaller, which could be highlighted in the forward view. Out of service cables account for c. 14% of the length of cables worldwide and have no live current and hence also have no electromagnetic field.
- Repeatered (powered) telecommunication systems do have a live current, but electrical fields are shielded and currents are markedly lower than power transmission cables - with an electro-magnetic field less than a lap-top computer. Magnetic fields induced by fibre optic cable powering are on the order of 30 to 38 microtesla (µT) at the cable surface. These values are lower than the background magnetic field produced by the Earth (60 µT). At 1 metre from the cable the magnetic field would be .30 to .38 µT or 1/100th of what it is at the surface of the cable (for example). This is therefore very different to power cables.

(See Table 2 on the following page).

Contamination

A recent study focused on surface-laid telecommunications cables is relevant to this point (Carter et al., 2019). Cables laid on the deep seafloor for more than 38 years were found to be near-pristine. The stranded steel that provides strength to the cable was free of corrosion. Chemical analysis in the laboratory that subjected cables to different environmental conditions also found that deep sea cables are chemically inert. Such is the condition of these cables that they are targets for recycling for their high-grade plastic, steel, and copper components. Intentionally damaged sections of cables with protective metallic armour (the type installed

	Physical habitat			Invertebrates			Fish			Elasmobranch and Diadromous Fish			Marine mammals		
Installation / Decomissioning / Maintenance	Bur	LD	Dyn	Bur	LD	Dyn	Bur	LD	Dyn	Bur	LD	Dyn	Bur	LD	Dyn
Seabed disturbance	①	①		①	①		②	①							
Sediment resuspension	①			①	①		①	①		①	①				
Chemical pollution				①	①	①	①	①	①	①	①	①	①	①	①
Underwater noise				②	②	②	①	①	①	①	①	①	①	①	①
Operation	Bur	LD	Dyn	Bur	LD	Dyn	Bur	LD	Dyn	Bur	LD	Dyn	Bur	LD	Dyn
Reef effect		①	②		①	②		①	②		①	②			
Reserve effect	①	①	①	①	①	①	①	①	①	①	①	①	①	①	①
Chemical pollution				①	①	①	①	①	①	①	①	①	①	①	①
Electromagnetic fields				③	③	③	②	②	③	②	②	③			②
Heat emission				②	①	①									
Entanglement									②			②			②

Extent of impact: Negligible | Low | Medium | High

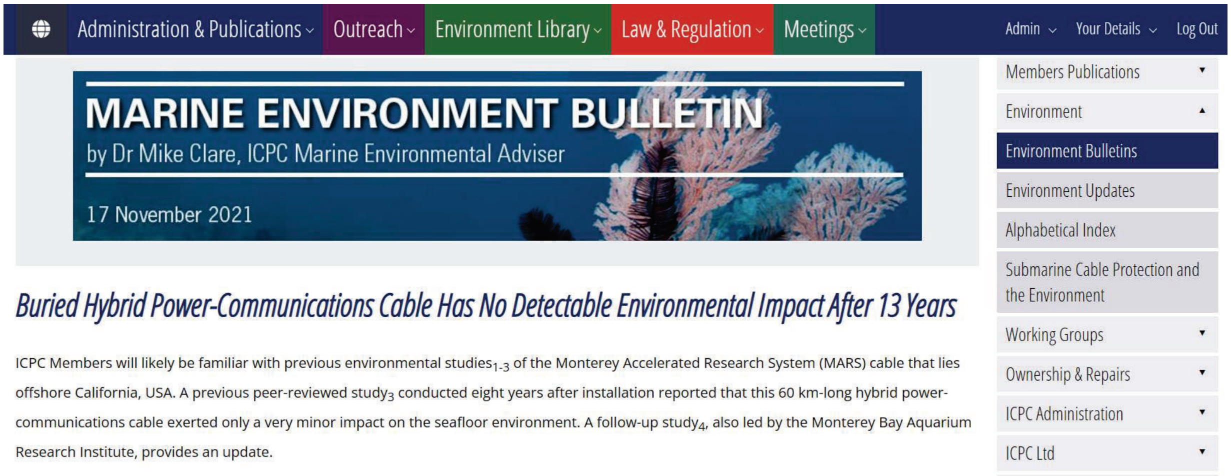
Uncertainty: ① Low ② Medium ③ High

▲ **Table 2: Synthesis of the importance of potential impacts caused by submarine power cables on different marine compartments during installation, operation, maintenance and decommissioning, based on the author's interpretation of the reviewed literature. For each interaction, the extent of the impact and associated uncertainty are quantified as 'Negligible', 'Low', 'Medium' or 'High'. Bur = Buried SPC. Black fill = no impact. From Taormina et al., (2018).**

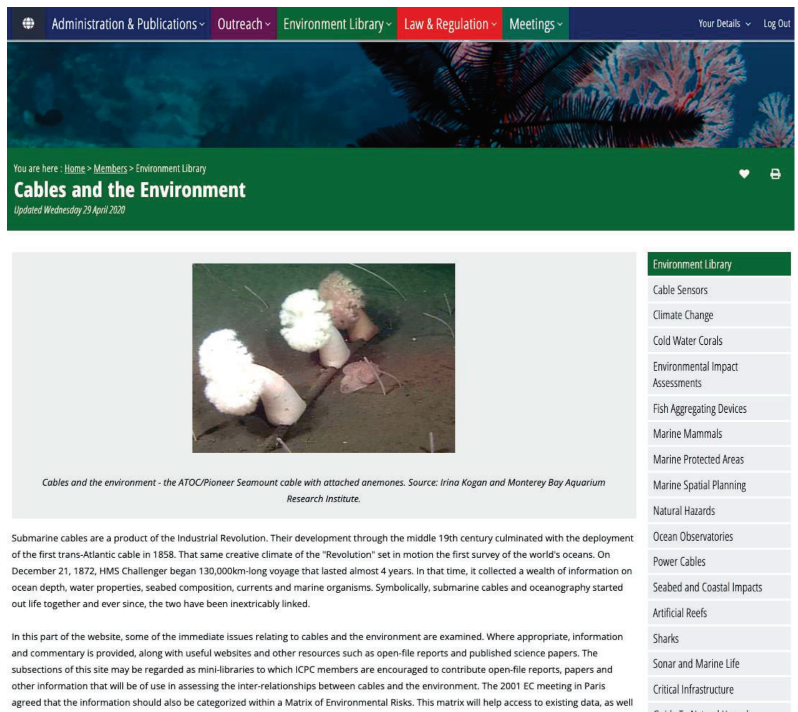
in shallower water) were found to temporarily release low concentrations of zinc (<11 parts per million). These low concentrations observed recorded in the small, contained experiment would be significantly further diluted within the open ocean, particularly due to the action of currents that sweep across the seafloor.

Closing remarks

Clearly this review provides a snapshot in time, and the state of knowledge will keep evolving. As a result, the ICPC's Marine Environmental Advisor (MEA) maintains a watching brief on new scientific developments, and will continue to report timely updates through the issue of *Marine Environment Bulletins.* (in the Members area under 'Administration & Publications). ICPC Members are also reminded of the extensive resources that are available to them in the ICPC *Environment Library* which can be accessed via the Member's Area.



There are many areas where additional environmental data could help to fill outstanding knowledge gaps and provide the basis for future studies. ICPC Members are encouraged to get in touch with the Marine Environmental Advisor if they have any suggestions for future studies, can provide access to environmental data (e.g. pre and post-lay surveys), or have specific queries about the environmental effects of cable-related activities.



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37. Also see a synopsis of studies by the US Navy Research Office: 'Studying the impact of seafloor cables on the marine environment' https://www.escaeu.org/download/?Id=329&source=documents

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Appendix 2 – EMF Modelling Report

Cable Consulting International Ltd

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29 July 2022.

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TITLE:	Sun Cable Influence Study
REPORT No:	ER1254

CUSTOMER:	Sun Cable
PROJECT No:	1124
AUTHOR:	David Notman BSc, CEng, MIET
DATE:	29 July 2022

Summary

The interaction of the AAPowerLink HVDC cable system with the surrounding environment has been assessed.

EMF calculations at 21 different locations have shown that field intensities as a result of the presence of the cable system are well within internationally recognized guidelines.

Thermal calculations have shown that heat produced by the cable system and resulting localised increases in surrounding temperatures are typical of those for similarly rated HVDC interconnectors such as those in service and being constructed in European waters.

Distribution: Sun Cable

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Registered office: 74 College Road, Maidstone, Kent, ME15 6SL, United Kingdom

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Issue	Date	Author	Reviewed	Revisions
0	06 Apr 22	DAN	LRT	Initial draft for comment
1	04 May 22	DAN	LRT	Updated draft for comment
2	29 July 22	DAN	LRT	Update that addresses Sun Cable's Rev 1 comments

1 Introduction

Cable Consulting International Limited (**CCI**) was engaged by Sun Cable on 09 February 2022 to assess how the AAPowerLink cable system will impact the local environment from electromagnetic and thermal points of view.

This version is Revision 2 of the report, and it addresses all the Sun Cable Revision 1 comments that were received on 31 May 2022.

This report is structured as follows:

- Section 2 covers electromagnetic field impacts.
- Section 3 covers the effect of electromagnetic fields on people and sealife.
- Section 4 covers thermal impacts.
- Section 5 covers cable crossing thermal resistivity.

2 Electromagnetic Field Calculations

2.1 General

When power flows through an HVDC cable during normal system operation, electric and magnetic fields are generated.

The electric field is the result of the cable's operating voltage, which is 525kV for the AAPowerLink system, and it is fully contained within the cable insulation by the semi-conducting screens that are bonded to the inner and outer surfaces of the cable. No part of the electric field escapes outside of the cable.

The magnetic field is the result of the electric current that flows along the cable conductor. The field extends outside of a cable and it is usual to express the magnitude of the field in terms of flux density, which has units of Tesla. An alternative expression for flux density is field intensity and this term is used in the remainder of this report.

The magnetic field intensity is dependent on the electrical current that flows in the cable and the distance from the cable:

- As current increases, the intensity increases.
- As distance from the cable increases, the intensity decreases.

The AAPowerLink subsea cable system comprises two 525kV pole cables and a lower voltage metallic return cable. The cables are planned to be installed in two standard configurations and these are explained in Section 2.2 below.

Calculation inputs and outputs are given in Section 2.3 below.

There is a magnetic field present in the earth that is called the geomagnetic (**GM**) field. This is explained in Section 2.4 below.

How the magnetic fields generated by the cables are calculated is explained in Section 2.5.

The cable and GM fields interact with each other and how they combine is explained in Section 2.6.

When something such as seawater or marine life moves through a magnetic field (either through the field from the cable or through the GM field) an electric field is induced in the object. This is explained in Section 2.8.

All calculations have been performed using steady state, continuous conditions. Calculations for harmonics, transient conditions and fault conditions have not been performed.

2.2 Cable Configurations

There are two cable configurations: Spaced and bundled.

The spaced configuration is shown in Figure 1.

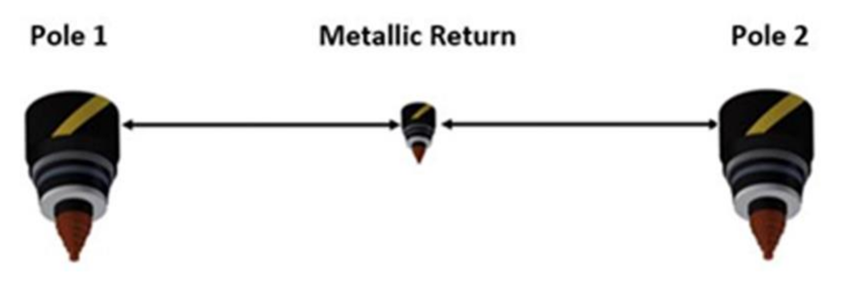

Figure 1 – Spaced Configuration

In the spaced configuration the cables are at least 50 metres apart. When the system is fully commissioned, electric current will flow in the Pole 1 and Pole 2 cables[a]. Before full commissioning, electric current will flow in the Pole 1 and Metallic Return cables. Only two cables will carry current at any one time.

[a] A very small current may flow in the return cable, but this can be ignored.

The currents that flow in the two cables flow in opposite directions and this results in some cancelling of the net magnetic field at any particular point of interest. The lower the spacing between two cables, the greater is the cancelling effect.

The AAPowerLink cables are spaced at least 50m apart and here, and at greater spacings, the cancelling effect is negligible. For this reason, calculations have only been performed for the worst case of one single cable in isolation.

The bundled configuration 2 is shown Figure 2.

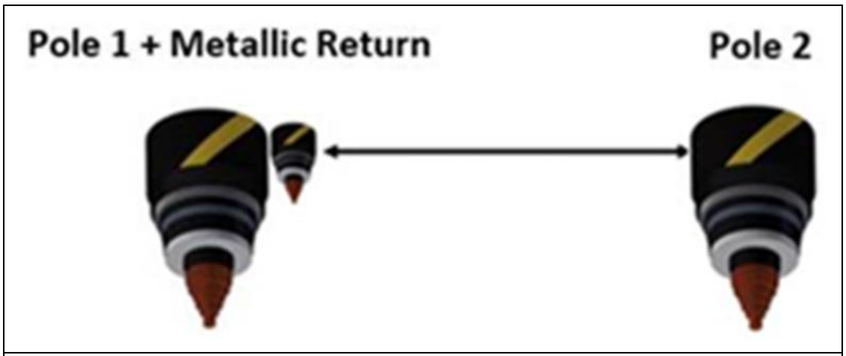

Figure 2 – Bundled Configuration

The AAPowerLink system will be operated in the bundled configuration before Pole 2 has been installed and in the event that Pole 2 is unavailable.

As the Pole 1 and Metallic Return cables are touching each other, the cancelling effect for the currents flowing in opposite directions is significant so is taken into account in the calculations.

2.3 Calculation Inputs and Outputs

2.3.1 Inputs

Cable currents are as follows:

- Spaced configuration, 1,950A in each cable
- Bundled configuration, 683A in each cable

Calculations have been performed at 21 different locations along the AAPowerLink route, starting at the Australian end and moving towards Singapore. These are shown in Figure 3.

Figure 3 – Marker Locations

Table 1 shows details of each marker location.

Marker	Water Depth [m]	Latitude[°]		Longitude[°]		ECS	Cable Depths [m]	Configuration
1	12	12.27795155	S	130.75341392	E	2	0.0, 1.0, 2.0	Spaced and Bundled
2	26	12.27299949	S	130.49877964	E	3	5.0	
3	68	11.96621221	S	129.38326808	E	4	0.0, 1.0, 2.0	
4	123	11.88296104	S	127.39944085	E	4	0.0, 1.0, 2.0	
5	114	12.04020878	S	124.99650192	E	5	0.0	Spaced
6	800	11.34901370	S	122.69093277	E	5	0.0	
7	500	11.00510552	S	121.23696748	E	5	0.0	
8	150	9.89100520	S	119.68758045	E	6	0.0, 1.0, 2.0	Spaced and Bundled
9	600	9.08201691	S	117.51746456	E	6	0.0, 1.0, 2.0	
10	30	9.04794443	S	116.78992167	E	6	0.0, 1.0, 2.0	
11	160	8.97427178	S	116.23598368	E	6	0.0, 1.0, 2.0	
12	100	8.54566780	S	115.87509086	E	6	0.0, 1.0, 2.0	
13	400	7.02348357	S	116.52614970	E	6	0.0, 1.0, 2.0	
14	75	6.18062839	S	114.88118866	E	6	0.0, 1.0, 2.0	
15	50	4.85746312	S	110.25726466	E	6	0.0, 1.0, 2.0	
16	35	2.92824866	S	107.30347484	E	6	0.0, 1.0, 2.0	
17	22	1.08912774	N	104.2014475	E	6	0.0, 1.0, 2.0	
18	45	1.23343793	N	104.0569201	E	7	0.0, 1.0, 2.0	
19	35	1.20306415	N	103.8557594	E	7	0.0, 1.0, 2.0	
20	15	1.24169173	N	103.704271	E	8	12.0	
21	33	1.22181042	N	103.78827375	E	9	10.0	

Table 1 – Marker Locations

In Table 1, the column titled 'ECS' is the environmental conditions section within which each marker location lies, see Figure 44 in Appendix 1.

The column titled 'Cable Depths' is burial depths to the top of the cable. Where a depth is 0.0m, the cable is sitting on the seabed surface. Calculations have been performed for each of the depths in the table.

The column titled 'Configuration' indicates where spaced and bundled or just spaced calculations have been performed.

2.3.2 Outputs

Calculations have been performed at the 21 marker locations for the cable burial depths and configurations shown in Table 1.

For each set of inputs, the magnetic fields at seabed level and 1 metre above seabed level were calculated.

Calculations were performed in three stages:

- Calculate the GM field
- Calculate the field resulting from the cable(s)
- Calculate the combined cable and GM field

Taking Marker 1 as an example, calculation results for the three stages are shown in Sections 2.4 to 2.6 below along explanations of how the calculations were performed.

Charts showing results for all marker locations are shown in Appendix 3.

2.4 Geomagnetic Field

The geomagnetic (**GM**) field measured at any point on the earth's surface is a combination of several magnetic fields generated by various sources. These fields are superimposed on, and interact with, each other.

The GM field is a vector in that it has a magnitude and a direction. It is described by seven parameters. They are declination (D), inclination (I), horizontal intensity (H), vertical intensity (Z), total intensity (F) and the north (X) and east (Y) components of the horizontal intensity.

The British Geological Survey[1] (**BGS**), National Oceanic and Atmospheric Administration[2] (**NOAA**) and Geoscience Australia[3] (**GA**) web sites are good sources for further information.

The GM field components are shown in Figure 4[2].

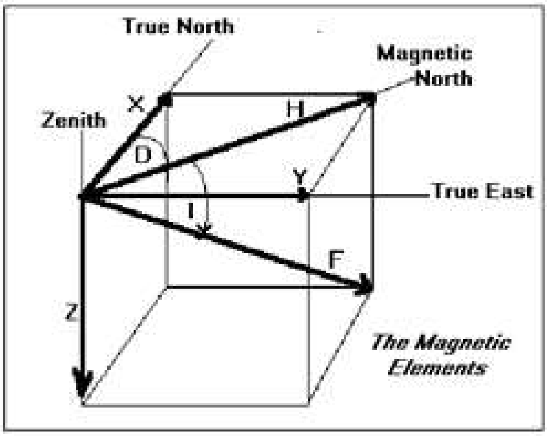

Figure 4 – GM Field Components

By convention[2]:

- Declination is positive when it is measured east of north
- Inclination and vertical intensity are positive in the downward direction
- The X axis is positive in the northern direction
- The Y axis is positive in the eastern direction
- The Z axis is positive in the downward direction

The GM field changes with time and location. The simplest way to make comparisons is to compare the total intensity, which is 'F' in Figure 4.

The NOAA web site provides online calculators[4] that can be used to calculate the field intensity and components of the GM field at a particular latitude, longitude and elevation on a given date. The World Magnetic Model (**WMM**) has been used to calculate the GM field at the 21 marker locations on 31 December 2024. The date was selected as it is the latest date for which calculations are available and is therefore the closest date to the AAPowerlink commissioning dates.

The required inputs for the WMM and the outputs it produces are shown in Figure 5[2]

The input parameters and valid entries are:

Latitude -90.00 to +90.00 degrees
Longitude -180.00 to +180.00 degrees
Altitude -1 to 850km referenced to the WGS 84 ellipsoid OR the Mean Sea Level (MSL)
Date 2020.0 to 2025.0

The seven magnetic components computed are:

F - **Total Intensity** of the geomagnetic field
H - **Horizontal Intensity** of the geomagnetic field
X - **North Component** of the geomagnetic field
Y - **East Component** of the geomagnetic field
Z - **Vertical Component** of the geomagnetic field
I (DIP) - **Geomagnetic Inclination**
D (DEC) - **Geomagnetic Declination** (Magnetic Variation)

Figure 5 – WWM Inputs and Outputs

Using the WMM calculator, the GM field and its components at Marker 1 (Australia end of the route) on 31 December 2024 were calculated and results are shown in Figure 6. The 'Total Field' column is the field intensity.

Magnetic Field

Model Used:	WMM-2020
Latitude:	12.27795155° S
Longitude:	130.75341392° E
Elevation:	-12.0 m Mean Sea Level

Date	Declination (+ E | - W)	Inclination (+ D | - U)	Horizontal Intensity	North Comp (+ N | - S)	East Comp (+ E | - W)	Vertical Comp (+ D | - U)	Total Field
2024-12-31	2.1333°	-39.2485°	35,745.4 nT	35,720.6 nT	1,330.6 nT	-29,203.7 nT	46,158.3 nT
Change/year	-0.0808°/yr	-0.0052°/yr	5.8 nT/yr	7.6 nT/yr	-50.2 nT/yr	-10.2 nT/yr	10.9 nT/yr
Uncertainty	0.30°	0.21°	128 nT	131 nT	94 nT	157 nT	145 nT

Figure 6 – GM Field at Marker 1, Australia

By way of comparison, the GM Field and its components at Marker 21 (Singapore end of the route) are shown in Figure 7.

Magnetic Field

Model Used:	WMM-2020
Latitude:	1.22181042° N
Longitude:	103.78827375° E
Elevation:	-33.0 m Mean Sea Level

Date	Declination (+ E | - W)	Inclination (+ D | - U)	Horizontal Intensity	North Comp (+ N | - S)	East Comp (+ E | - W)	Vertical Comp (+ D | - U)	Total Field
2024-12-31	0.0235°	-13.2147°	41,123.7 nT	41,123.7 nT	16.9 nT	-9,656.6 nT	42,242.3 nT
Change/year	-0.0260°/yr	0.1297°/yr	40.5 nT/yr	40.6 nT/yr	-18.6 nT/yr	88.7 nT/yr	19.2 nT/yr
Uncertainty	0.29°	0.21°	128 nT	131 nT	94 nT	157 nT	145 nT

Figure 7 – GM Field at Marker 21, Singapore

It can be seen that the field is higher in Australia than in Singapore.

In Figure 6 and Figure 7 the units for the GM field components are nT, which is nano Tesla. For comparison with the fields generated by the cables, which have units of µT (micro Tesla), the GM values should be divided by 1,000. For example, the total field in Australia is 46,158.3nT and this is 46.16µT.

In both Australia and Singapore, the vertical component of the field is negative. This means that it is pointing upwards and not downwards as is shown in Figure 4. This is because the drawing in Figure 4 is a North American drawing and, there, the field does point downwards.

The field intensities and components for the 21 marker locations on 31 December 2024 calculated using the WMM are shown in Appendix 2.

2.5 Cable Field

With reference to Figure 4 above, cables sit in the YZ plane.

Figure 8 shows two cables in the YZ plane. The cables are assumed to run north to south. Cable 1 is carrying a positive current and the current is assumed to flow out of the page. Cable 2 is carrying a negative current and the current is assumed to flow into the page. The current flows are as expected for the AAPowerLink cables: For both the spaced and bundled configurations, the current flows in one direction in one cable and in the opposite direction in the other cable.

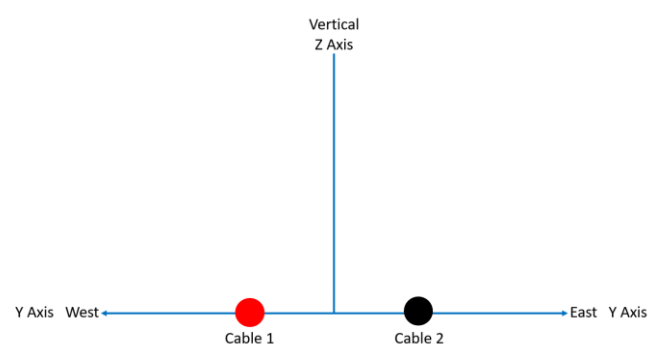

Figure 8 – Cables in YZ plane

The magnitude of the magnetic field from a long straight wire at a point of interest is given by Ampere's Law:

$$B = \frac{\mu_0 I}{2\pi r} \text{ Tesla}$$

where μ_0 = permeability of free space = 4π x 10^{-7} Henries per metre
I = current in Amperes
r = distance from the centre of the wire to the point of interest in metres

The direction of the field from a cable is given by the Right-Hand Rule, Figure 9.

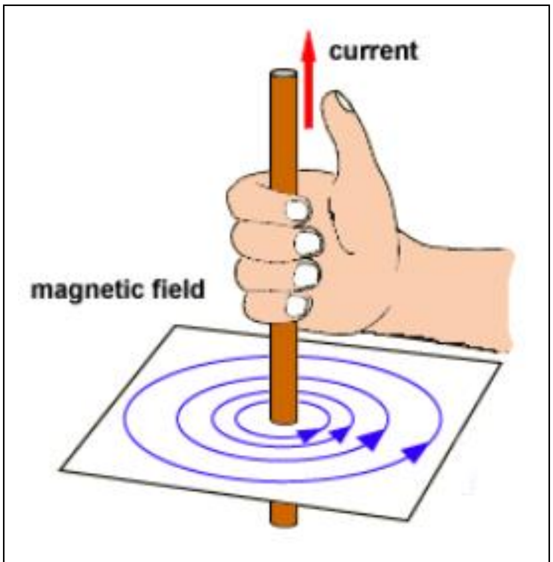

Figure 9 – Right-Hand Rule

When two cables are present, the fields from the two cables interact with each other. The Cable 1 and Cable 2 field intensities are resolved into their Y (horizontal) and Z (vertical) components, the Y and Z components are summed and then the resultant field intensity is calculated. This is shown diagrammatically in Figure 10.

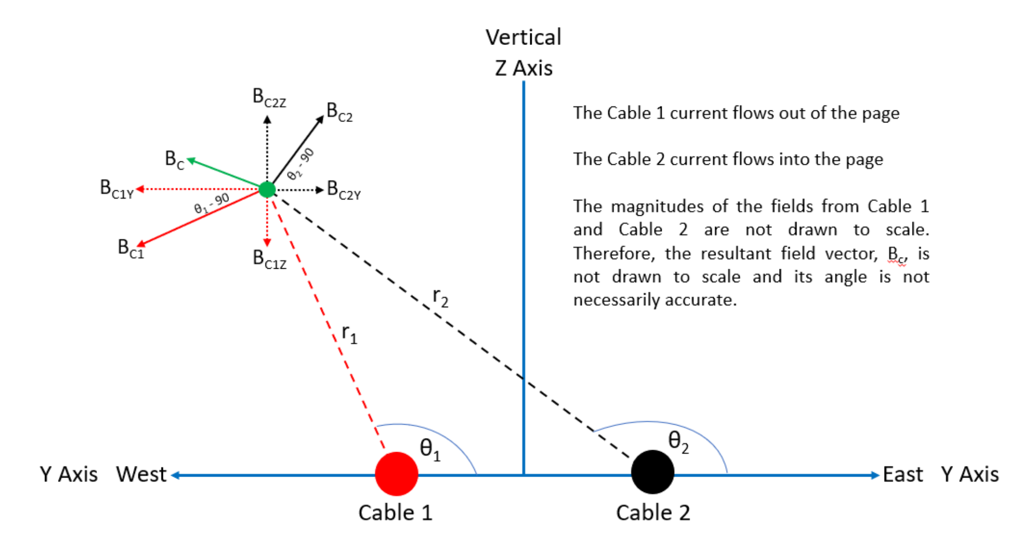

Figure 10 – Resultant Cable Field

In the case of the AAPowerLink spaced configuration, the cables are spaced at least 50m apart so the interaction between the two cables at any particular point of interest is minimal and can be ignored.

Cable circuits do not always run north to south. When only the influence of the field from the cables is being considered and the geomagnetic components are ignored, the direction in which the cable circuit runs does not matter.

It is only when the combined effect of the cable and geomagnetic fields is considered that the circuit direction matters, and this is explained in Section 2.6.

Taking the spaced cable configuration as an example (where the cable current is 1,950A and one single pole cable is considered), Figure 11 shows the magnetic field intensities at the cable surface and 1m above the cable surface when the cable is sitting on the seabed surface. The field intensities are those that just result from the cable.

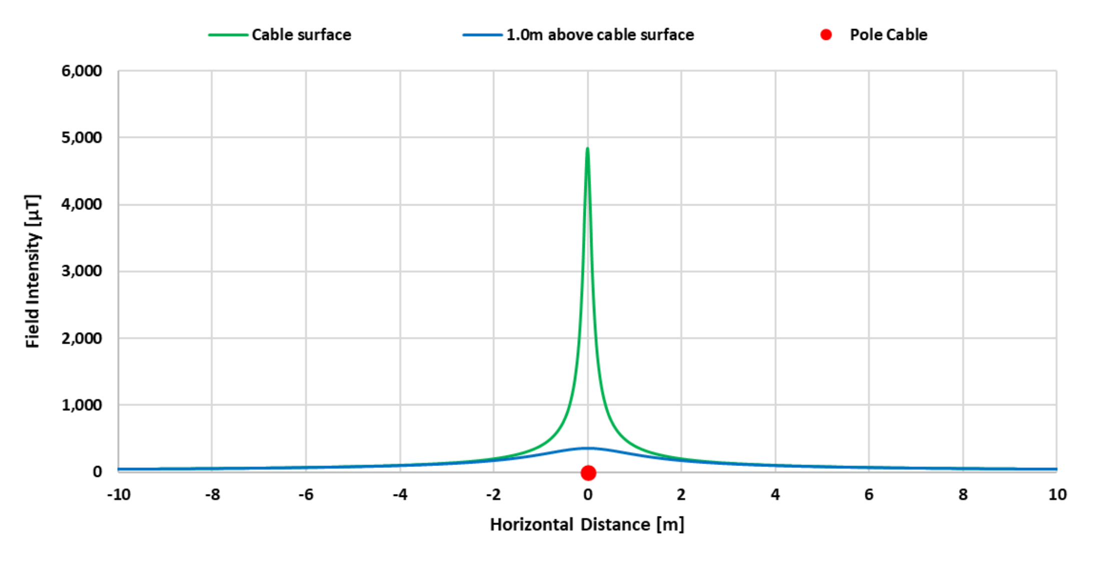

Figure 11 – Cable Sitting on Seabed Surface – Spaced Configuration

In Figure 11, the maximum field intensities are as follows:

- 4,844.7µT at the cable surface
- 360.9µT at 1m above the cable surface

Figure 12 shows the field intensities at the seabed surface and 1m above the seabed surface when the cable is buried at a depth of 1m to the top of the cable.

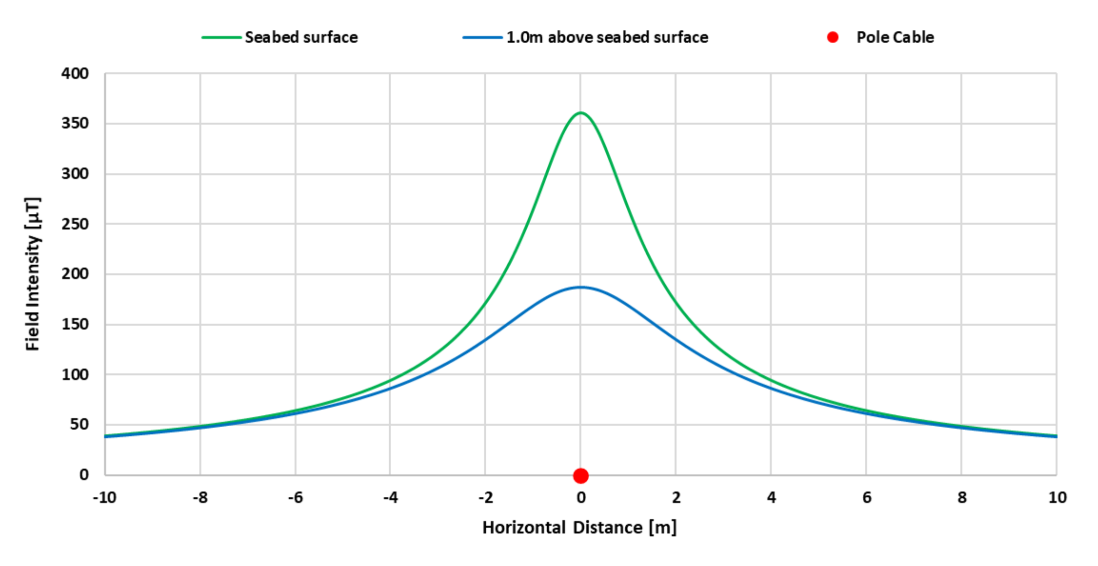

Figure 12 – Cable Buried at 1m to Top of Cable – Spaced Configuration

In Figure 12, the maximum field intensities are as follows:

- 360.9µT at the cable surface
- 187.5µT at 1m above the cable surface

Figure 13 shows the field intensities at the seabed surface and 1m above the seabed surface when the cable is buried at a depth of 2m to the top of the cable.

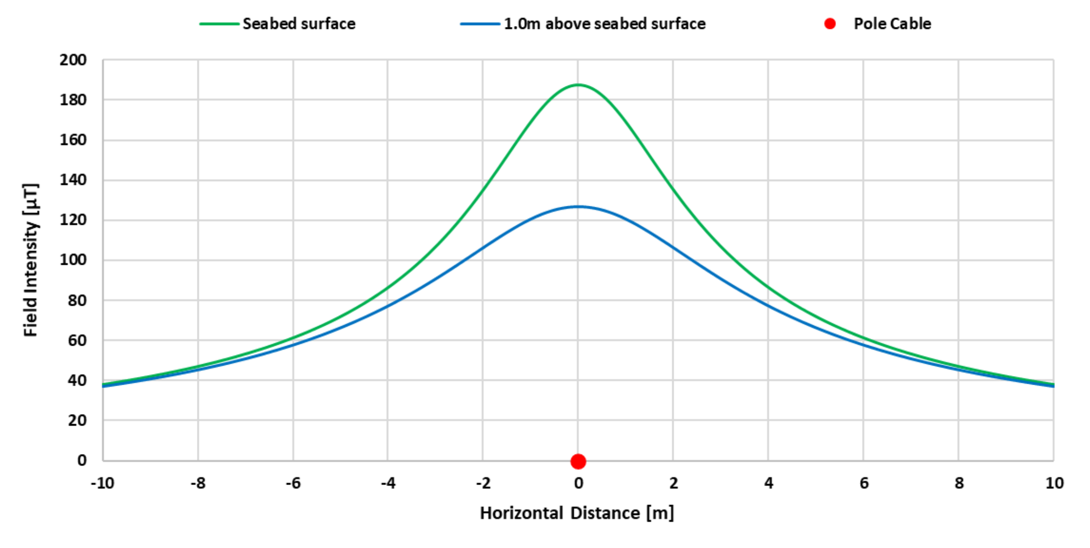

Figure 13 – Cable Buried at 2m to Top of Cable – Spaced Configuration

In Figure 13, the maximum field intensities are as follows:

- 187.5µT at the cable surface
- 126.6µT at 1m above the cable surface

In Figure 11 to Figure 13 the field intensities decrease as the horizontal distance away from the cable increases.

At a horizontal distance of 100m away, the field intensity reduces to 3.9µT in all cases.

If the cables are bundled (where the cable current is 683A and flows in the two cables in opposite directions) there is interaction between the magnetic fields generated by the cables which results in a cancelling effect and reduction in the field intensities.

Figure 14 shows the magnetic field intensities at the cable surface and 1m above the cable surface when the bundled cables are sitting on the seabed surface. The field intensities are those that just result from the cables.

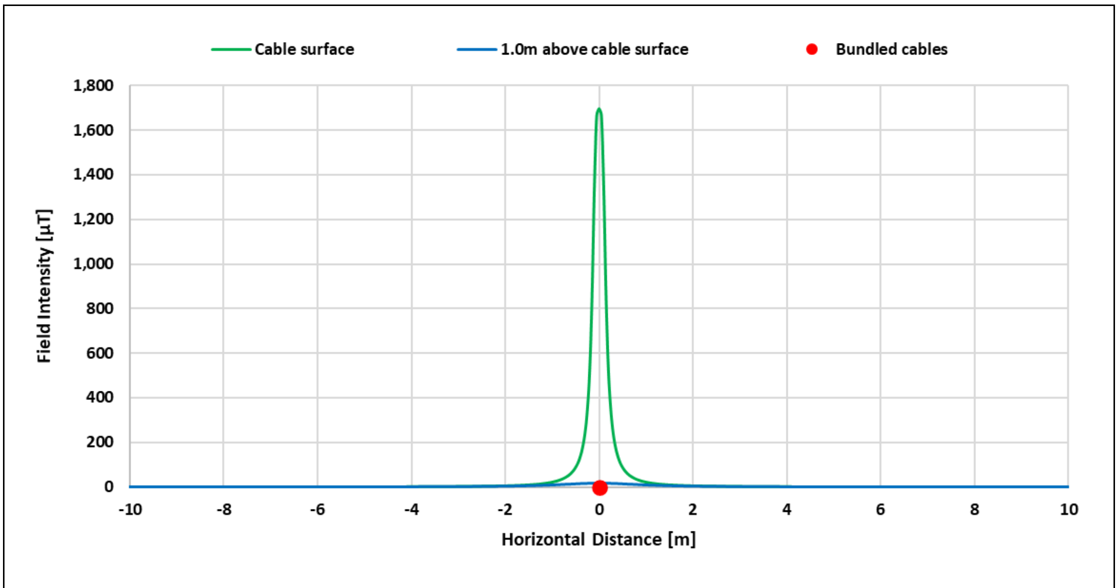

Figure 14 – Cable Sitting on Seabed Surface – Bundled Configuration

In Figure 14, the maximum field intensities are as follows:

- 1,696.9µT at the cable surface
- 18.7µT at 1m above the cable surface

Figure 15 shows the field intensities at the seabed surface and 1m above the seabed surface when the bundled cables are buried at a depth of 1m to the top of the cable.

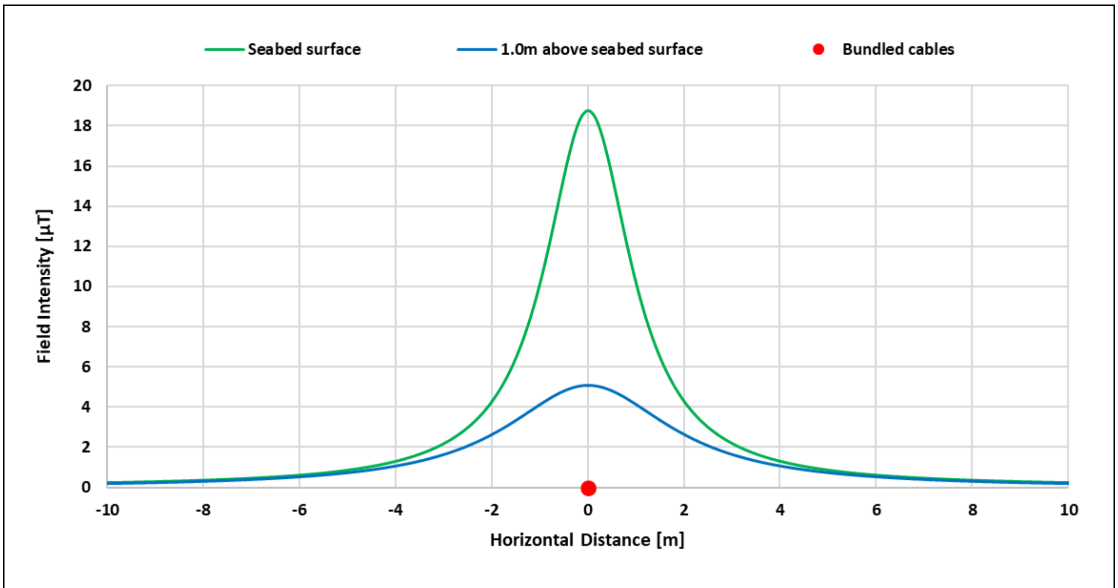

Figure 15 – Cable Buried at 1m to Top of Cable – Bundled Configuration

In Figure 15, the maximum field intensities are as follows:

- 18.7µT at the cable surface
- 5.1µT at 1m above the cable surface

Figure 16 shows the field intensities at the seabed surface and 1m above the seabed surface when the bundled cables are buried at a depth of 2m to the top of the cable.

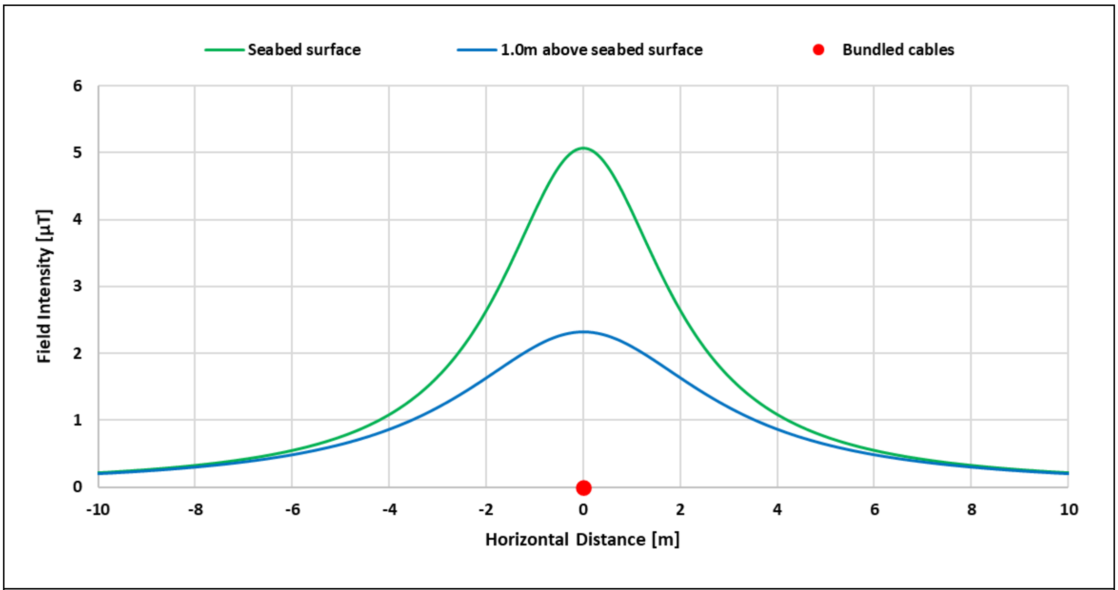

Figure 16 – Cable Buried at 2m to Top of Cable – Bundled Configuration

In Figure 16, the maximum field intensities are as follows:

- 5.1µT at the cable surface
- 2.3µT at 1m above the cable surface

At a horizontal distance of 100m away from the bundle, the field intensity reduces to 0.002µT.

2.6 Combined Cable and Geomagnetic Field

Assuming the cables are straight and running north to south (for the time being), the magnetic field from the cables is in the YZ plane, see Figure 8 above.

The Y direction is horizontal (east is positive and west is negative) and the Z direction is vertical (down is positive and up is negative). At any point of interest the cable field intensity can be resolved into its Y and Z components.

The GM field has an X component (north is positive and south is negative) as well as Y and Z components, see Figure 4.

To demonstrate how the cable and GM fields combine, the following example is used:

- A spaced cable configuration is used (where spacing is at least 50m so interaction between the two cables can be ignored and only one single cable is considered).

- The cable current is 1,950A and the cable is buried at a depth of 1m to its top.

- The field intensities from only the cable are shown at seabed level and 1m above seabed level in Figure 12. The influence from the GM field is not shown in Figure 12. The intensities resulting from the cable vary with horizontal distance away from the cable. The field intensities from the cable at 1m above seabed level at horizontal distances of ±2m away from the cable are considered in this example and are:
  - -2m horizontal distance away from the cable, intensity = 135.14µT
  - +2m horizontal distance away from the cable, intensity = 135.14µT

- At the horizontal distance of -2m away from the cable, the Y (horizontal, eastern) and Z (vertical) components of the field from the cable are:
  - Y = -97.42µT (points west)
  - Z = +93.65µT (points down)

- At the horizontal distance of +2m away from the cable, the Y (horizontal, eastern) and Z (vertical) components of the field from the cable are:
  - Y = -97.42µT (points west)
  - Z = -93.65µT (points up)

- At the two points, the intensities of the horizontal and vertical components from the cable are identical, but the directions of the vertical components are opposite. One way to think about what is happening is to consider the right-hand rule that is shown in Figure 9: The point -2m away is to the left of the cable and +2m away is to the right.

- Now the influence of the GM field is considered. The physical location is at Marker 1. The GM field at this location and in its immediate vicinity is assumed to be constant.

- With reference to Figure 6, and converting figures from nano Tesla to micro Tesla by dividing by 1,000, the GM field at Marker 1 is described as follows:
  - The total intensity is 46.16µT
  - The X (northern) component is +35.72µT
  - The Y (eastern) component is +1.33µT
  - The Z (vertical) component is -29.20µT

Table 2 shows the components of the cable field, the GM field and the combined field at the horizontal distance of -2m away from the cable.

-2m horizontal away from the cable			
Field	**X Component**	**Y Component**	**Z Component**
Cable	0.00µT	-97.42µT	+93.65µT
GM	+35.72µT	+1.33µT	-29.20µT
Total	**+35.72µT**	**-96.09µT**	**64.45µT**

Table 2 – Combined Field -2m Away from Cable

The combined (i.e. resultant) intensity at the horizontal distance -2m away from the cable is 121.09µT and this is calculated by squaring the total X, Y and Z components, summing them and taking the square root.

Table 3 shows the components of the cable field, the GM field and the combined field at the horizontal distance of +2m away from the cable.

+2m horizontal away from the cable			
Field	**X Component**	**Y Component**	**Z Component**
Cable	0.00µT	-97.42µT	-93.65µT
GM	+35.72µT	+1.33µT	-29.20µT
Total	**+35.72µT**	**-96.09µT**	**-122.85µT**

Table 3 – Combined Field +2m Away from Cable

The combined (i.e. resultant) intensity at the horizontal distance +2m away from the cable is 160.00µT.

Figure 17 shows how the combined field intensity varies over a horizontal range of ±10m away from the cable. The blue line is at a distance of 1.0m above the seabed surface (the example calculation results given above lie on this line) and the green line is at the seabed surface.

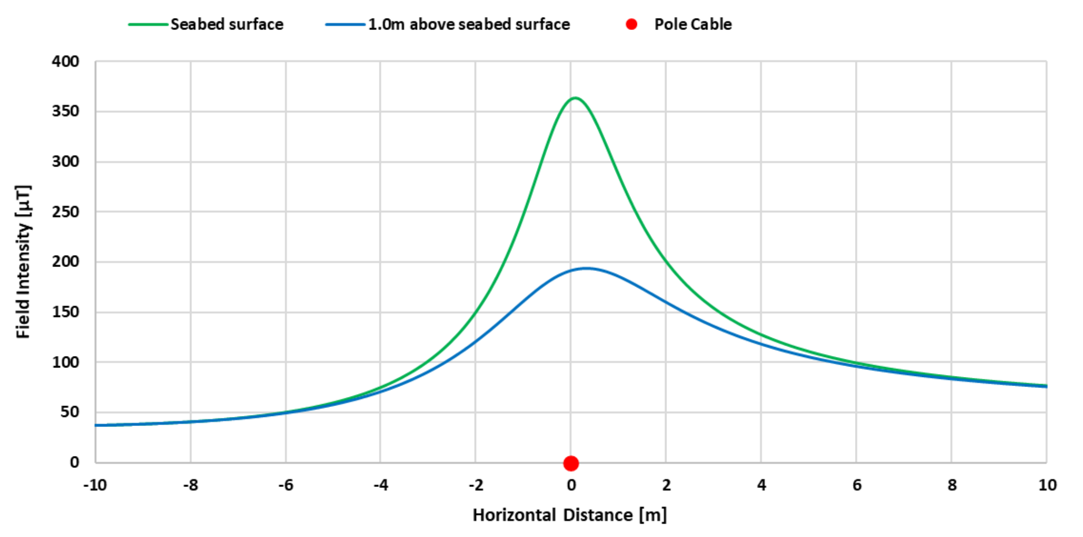

Figure 17 – Combined Field Intensity – Spaced Configuration

As the horizontal distance away from the cable increases beyond ±10m, the influence of the cable diminishes, and the field intensity trends to the GM intensity of 46.16µT.

The calculations so far in this section assume that the cables run north to south.

If the cables do not run north to south, the Z component (vertical) does not change but the horizontal intensity changes from just being the Y component (east) to being a Y component (east) and an X component (north), Figure 18.

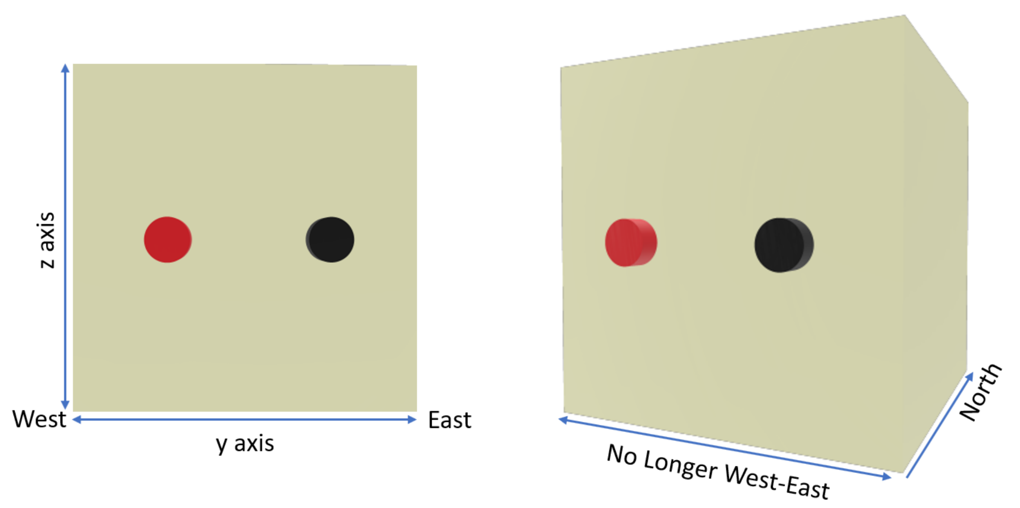

Figure 18 – Cable Circuit Rotation

Continuing with the example described above and considering a cable circuit rotation of 45°, the cable field intensity Y component before rotation must be resolved into Y and X components after the angle of rotation is taken into account.

- At the horizontal distance of -2m away from the cable
  - Before rotation Y = -97.42µT (points west), X = 0
  - After rotation Y = -68.89µT (points west), X = 68.89µT (points north)

- At the horizontal distance of +2m away from the cable
  - Before rotation Y = -97.42µT (points west), X = 0
  - After rotation Y = -68.89µT (points west), X = 68.89µT (points north)

Table 4 shows the components of the combined field at the horizontal distance of -2m away from the cable after the rotation of 45°.

-2m horizontal away from the cable			
Field	**X Component**	**Y Component**	**Z Component**
Cable	+68.89µT	-68.89µT	+93.65µT
GM	+35.72µT	+1.33µT	-29.20µT
Total	**+104.61µT**	**-67.56µT**	**64.45µT**

Table 4 – Combined Field -2m Away from Cable

The resultant intensity at the horizontal distance -2m away from the cable is 140.22µT.

Table 5 shows the components of the combined field at the horizontal distance of +2m away from the cable after the rotation of 45°.

+2m horizontal away from the cable			
Field	**X Component**	**Y Component**	**Z Component**
Cable	+68.89µT	-68.89µT	-93.65µT
GM	+35.72µT	+1.33µT	-29.20µT
Total	**+104.61µT**	**-67.56µT**	**-122.85µT**

Table 5 – Combined Field +2m Away from Cable

The resultant intensity at the at the horizontal distance +2m away from the cable is 174.93µT

Figure 19 shows how the combined field intensity varies over a horizontal range of ±10m away from the cable. The blue line is at a distance of 1.0m above the seabed surface (the example calculation results given above lie on this line) and the green line is at the seabed surface.

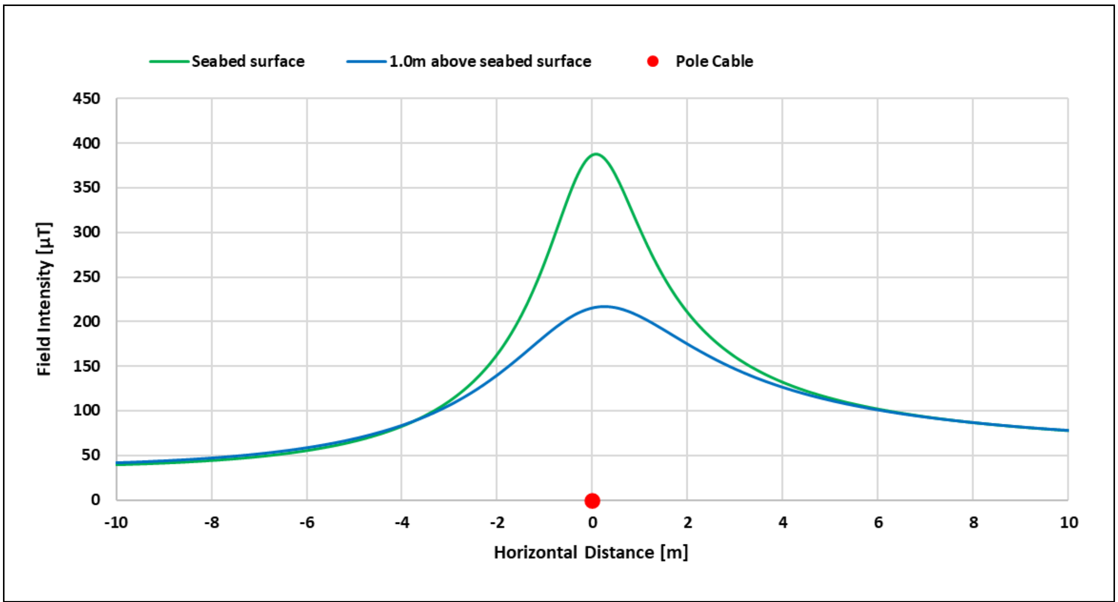

Figure 19 – Combined Field Intensity – Spaced Configuration, 45° Circuit Angle

As the horizontal distance away from the cable increases beyond ±10m, the influence of the cable diminishes, and the field intensity trends to the GM intensity of 46.16µT.

If, instead of 45°, the circuit is rotated by 90° then for the cable field:

- At the horizontal distance of -2m away from the cable
  - Before rotation Y = -97.42µT (points west), X = 0
  - After rotation Y = 0, X = 97.42µT (points north)

- At the horizontal distance of +2m away from the cable
  - Before rotation Y = -97.42µT (points west), X = 0
  - After rotation Y = 0 (points west), X = 97.42µT (points north)

Figure 20 shows how the combined field intensity varies over a horizontal range of ±10m away from the cable. The blue line is at a distance of 1.0m above the seabed surface (the example calculation results given above lie on this line) and the green line is at the seabed surface.

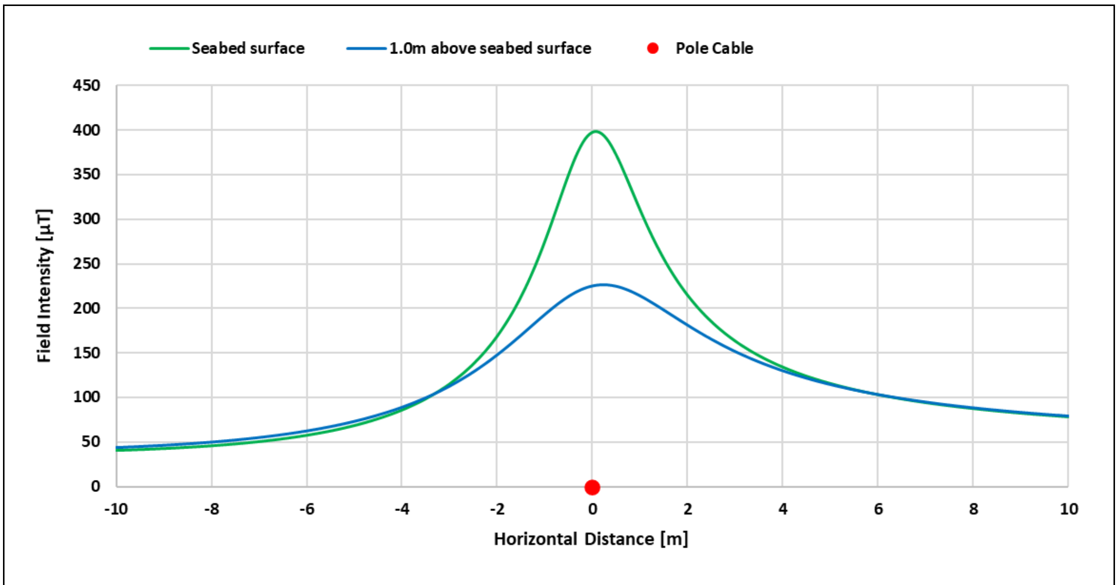

Figure 20 – Combined Field Intensity – Spaced Configuration, 90° Circuit Angle

2.7 Calculation Results

2.7.1 General

At each marker location calculations were performed at the cable depths and configurations shown in Table 1 above.

The calculations were performed for the following cable circuit angles:

- 0°: The cables run north to south
- 45°: The cables run northeast to southwest
- 90°: The cables run east to west
- -45°: The cables run northwest to southeast

The maximum combined cable/GM field intensity for each calculation is shown in the tables in Sections 2.7.2 to 2.7.9 below.

2.7.2 Spaced Configuration – Cables on Seabed Surface

Marker	Maximum Intensities at Different Circuit Angles [µT]							
	Cable Surface				1.0m Above Cable Surface			
	0°	45°	90°	-45°	0°	45°	90°	-45°
1	4,843.6	4,869.2	4,880.5	4,818.7	363.7	388.1	398.5	338.4
2	Not required				Not required			
3	4,843.8	4,869.5	4,880.7	4,818.6	363.8	388.3	398.7	338.3

Marker	Maximum Intensities at Different Circuit Angles [μT]							
	Cable Surface				1.0m Above Cable Surface			
	0°	45°	90°	-45°	0°	45°	90°	-45°
4	4,844.0	4,869.7	4,880.9	4,818.7	364.0	388.5	398.8	338.3
5	4,844.1	4,869.9	4,881.0	4,818.7	364.2	388.7	398.9	338.4
6	4,844.3	4,870.2	4,881.4	4,818.5	364.3	389.0	399.2	338.1
7	4,844.3	4,870.4	4,881.5	4,818.5	364.3	389.2	399.4	338.0
8	4,844.4	4,870.8	4,882.0	4,818.2	364.1	389.4	399.7	337.4
9	4,844.5	4,871.1	4,882.4	4,817.9	364.0	389.6	400.0	337.0
10	4,844.5	4,871.2	4,882.4	4,817.9	364.1	389.6	400.0	337.0
11	4,844.5	4,871.2	4,882.5	4,817.9	364.1	389.7	400.0	337.0
12	4,844.5	4,871.3	4,882.7	4,817.7	364.0	389.7	400.1	336.8
13	4,844.5	4,871.7	4,883.2	4,817.4	363.9	389.9	400.4	336.1
14	4,844.6	4,872.0	4,883.5	4,817.2	363.8	390.1	400.6	335.7
15	4,844.6	4,872.4	4,884.1	4,816.8	363.7	390.4	401.1	335.2
16	4,844.6	4,872.9	4,884.8	4,816.4	363.6	390.7	401.5	334.5
17	4,844.9	4,873.8	4,885.8	4,815.7	363.4	391.2	402.1	333.4
18	4,844.9	4,873.9	4,885.8	4,815.7	363.4	391.2	402.2	333.4
19	4,844.9	4,873.9	4,885.8	4,815.7	363.4	391.2	402.2	333.4
20	Not required				Not required			
21	Not required				Not required			

Table 6 – Maximum Combined Magnetic Field Intensity

2.7.3 Spaced Configuration – Cables Buried 1.0m Deep

Marker	Maximum Intensities at Different Circuit Angles [μT]							
	Seabed Surface				1.0m Above Seabed Surface			
	0°	45°	90°	-45°	0°	45°	90°	-45°
1	363.7	388.1	398.5	338.4	193.9	216.9	226.4	169.1
2	Not required				Not required			
3	363.8	388.3	398.7	338.3	194.0	217.1	226.5	168.9
4	364.0	388.5	398.8	338.3	194.2	217.3	226.7	168.9
5	Not required				Not required			
6	Not required				Not required			
7	Not required				Not required			
8	364.1	389.4	399.7	337.4	194.1	217.8	227.3	167.7
9	364.0	389.6	400.0	337.0	193.9	218.0	227.4	167.1
10	364.1	389.6	400.0	337.0	193.9	218.0	227.5	167.1
11	364.1	389.7	400.0	337.0	193.9	218.0	227.5	167.0

Marker	Maximum Intensities at Different Circuit Angles [µT]							
	Seabed Surface				1.0m Above Seabed Surface			
	0°	45°	90°	-45°	0°	45°	90°	-45°
12	364.0	389.7	400.1	336.8	193.8	218.0	227.5	166.7
13	363.9	389.9	400.4	336.1	193.4	218.0	227.6	165.7
14	363.8	390.1	400.6	335.7	193.3	218.1	227.8	165.2
15	363.7	390.4	401.1	335.2	193.1	218.3	228.1	164.4
16	363.6	390.7	401.5	334.5	192.8	218.5	228.4	163.4
17	363.4	391.2	402.1	333.4	192.4	218.8	228.9	161.7
18	363.4	391.2	402.2	333.4	192.4	218.8	228.9	161.7
19	363.4	391.2	402.2	333.4	192.4	218.8	228.9	161.7
20	Not required				Not required			
21	Not required				Not required			

Table 7 – Maximum Combined Magnetic Field Intensity

2.7.4 Spaced Configuration – Cables Buried 2.0m Deep

Marker	Maximum Intensities at Different Circuit Angles [µT]							
	Seabed Surface				1.0m Above Seabed Surface			
	0°	45°	90°	-45°	0°	45°	90°	-45°
1	193.9	216.9	226.4	169.1	136.6	157.8	166.5	113.2
2	Not required				Not required			
3	194.0	217.1	226.5	168.9	136.6	158.0	166.6	113.0
4	194.2	217.3	226.7	168.9	136.8	158.2	166.8	113.0
5	Not required				Not required			
6	Not required				Not required			
7	Not required				Not required			
8	194.1	217.8	227.3	167.7	136.4	158.5	167.2	111.3
9	193.9	218.0	227.4	167.1	136.2	158.6	167.3	110.6
10	193.9	218.0	227.5	167.1	136.2	158.6	167.3	110.6
11	193.9	218.0	227.5	167.0	136.2	158.6	167.3	110.5
12	193.8	218.0	227.5	166.7	136.0	158.6	167.3	110.1
13	193.4	218.0	227.6	165.7	135.5	158.5	167.3	108.7
14	193.3	218.1	227.8	165.2	135.2	158.5	167.4	108.0
15	193.1	218.3	228.1	164.4	134.9	158.6	167.7	106.9
16	192.8	218.5	228.4	163.4	134.5	158.7	167.9	105.5
17	192.4	218.8	228.9	161.7	133.8	158.8	168.1	103.1
18	192.4	218.8	228.9	161.7	133.8	158.8	168.2	103.0
19	192.4	218.8	228.9	161.7	133.8	158.9	168.2	103.0

Marker	Maximum Intensities at Different Circuit Angles [µT]							
	Seabed Surface				1.0m Above Seabed Surface			
	0°	45°	90°	-45°	0°	45°	90°	-45°
20	Not required				Not required			
21	Not required				Not required			

Table 8 – Maximum Combined Magnetic Field Intensity

2.7.5 Spaced Configuration – Cables Buried 5.0m, 10.0 and 12.0m Deep

The cable depths at the three markers are as follows:

- Marker 2: 5.0m
- Marker 20: 12.0m
- Marker 21: 10.0m

Marker	Maximum Intensities at Different Circuit Angles [µT]							
	Seabed Level				1.0m Above Seabed			
	0°	45°	90°	-45°	0°	45°	90°	-45°
2	88.5	108.5	116.2	74.1	78.0	96.8	104.1	66.5
20	53.2	68.6	74.0	39.9	51.7	66.4	71.6	39.1
21	57.3	74.4	80.4	42.2	55.0	71.2	76.9	40.9

Table 9 – Maximum Combined Magnetic Field Intensity

2.7.6 Bundled Configuration – Cables on Seabed Surface

Marker	Maximum Intensities at Different Circuit Angles [µT]							
	Cable Surface				1.0m Above Cable Surface			
	0°	45°	90°	-45°	0°	45°	90°	-45°
1	1,726.5	1,726.5	1,726.5	1,726.5	59.8	61.3	62.8	61.6
2	Not required				Not required			
3	1,726.1	1,726.1	1,726.1	1,726.1	59.6	61.2	62.7	61.4
4	1,726.0	1,726.0	1,726.0	1,726.0	59.6	61.3	62.7	61.4
5	Not required				Not required			
6	Not required				Not required			
7	Not required				Not required			
8	1,723.4	1,723.4	1,723.4	1,723.4	58.2	60.2	61.7	60.3
9	1,722.3	1,722.3	1,722.3	1,722.3	57.7	59.7	61.3	59.8
10	1,722.3	1,722.3	1,722.3	1,722.3	57.7	59.7	61.3	59.8
11	1,722.2	1,722.2	1,722.2	1,722.2	57.7	59.7	61.3	59.8
12	1,721.6	1,721.6	1,721.6	1,721.6	57.3	59.4	61.1	59.5

Marker	Maximum Intensities at Different Circuit Angles [µT]							
	Cable Surface				1.0m Above Cable Surface			
	0°	45°	90°	-45°	0°	45°	90°	-45°
13	1,719.2	1,719.2	1,719.2	1,719.2	55.9	58.2	60.0	58.3
14	1,718.0	1,718.0	1,718.0	1,718.0	55.2	57.7	59.6	57.8
15	1,716.3	1,716.3	1,716.3	1,716.3	54.5	57.2	59.2	57.3
16	1,713.6	1,713.6	1,713.6	1,713.6	53.1	56.2	58.3	56.3
17	1,707.2	1,707.2	1,707.2	1,707.2	50.0	54.1	56.5	54.1
18	1,707.0	1,707.0	1,707.0	1,707.0	49.9	54.0	56.5	54.0
19	1,707.1	1,707.1	1,707.1	1,707.1	50.0	54.1	56.5	54.1
20	Not required				Not required			
21	Not required				Not required			

Table 10 – Maximum Combined Magnetic Field Intensity

2.7.7 Bundled Configuration – Cables Buried 1.0m Deep

Marker	Maximum Intensities at Different Circuit Angles [µT]							
	Cable Surface				1.0m Above Cable Surface			
	0°	45°	90°	-45°	0°	45°	90°	-45°
1	59.8	61.3	62.8	61.6	49.5	50.1	50.6	50.2
2	Not required				Not required			
3	59.6	61.2	62.7	61.4	49.4	50.0	50.5	50.1
4	59.6	61.3	62.7	61.4	49.5	50.1	50.6	50.1
5	Not required				Not required			
6	Not required				Not required			
7	Not required				Not required			
8	58.2	60.2	61.7	60.3	48.5	49.2	49.8	49.3
9	57.7	59.7	61.3	59.8	48.1	48.9	49.5	48.9
10	57.7	59.7	61.3	59.8	48.2	48.9	49.5	48.9
11	57.7	59.7	61.3	59.8	48.2	48.9	49.5	48.9
12	57.3	59.4	61.1	59.5	47.9	48.7	49.3	48.7
13	55.9	58.2	60.0	58.3	46.9	47.8	48.4	47.8
14	55.2	57.7	59.6	57.8	46.5	47.4	48.1	47.4
15	54.5	57.2	59.2	57.3	46.1	47.1	47.8	47.1
16	53.1	56.2	58.3	56.3	45.3	46.4	47.2	46.5
17	50.0	54.1	56.5	54.1	43.7	45.2	46.0	45.2
18	49.9	54.0	56.5	54.0	43.7	45.1	46.0	45.1
19	50.0	54.1	56.5	54.1	43.7	45.2	46.0	45.2
20	Not required				Not required			

Marker	Maximum Intensities at Different Circuit Angles [µT]							
	Cable Surface				1.0m Above Cable Surface			
	0°	45°	90°	-45°	0°	45°	90°	-45°
21	Not required				Not required			

Table 11 – Maximum Combined Magnetic Field Intensity

2.7.8 Bundled Configuration – Cables Buried 2.0m Deep

Marker	Maximum Intensities at Different Circuit Angles [µT]							
	Cable Surface				1.0m Above Cable Surface			
	0°	45°	90°	-45°	0°	45°	90°	-45°
1	49.5	50.1	50.6	50.2	47.7	47.9	48.2	48.0
2	Not required				Not required			
3	49.4	50.0	50.5	50.1	47.5	47.8	48.1	47.9
4	49.5	50.1	50.6	50.1	47.6	47.9	48.2	47.9
5	Not required				Not required			
6	Not required				Not required			
7	Not required				Not required			
8	48.5	49.2	49.8	49.3	46.8	47.2	47.4	47.2
9	48.1	48.9	49.5	48.9	46.5	46.8	47.1	46.9
10	48.2	48.9	49.5	48.9	46.5	46.9	47.1	46.9
11	48.2	48.9	49.5	48.9	46.5	46.9	47.1	46.9
12	47.9	48.7	49.3	48.7	46.3	46.6	46.9	46.7
13	46.9	47.8	48.4	47.8	45.4	45.8	46.1	45.8
14	46.5	47.4	48.1	47.4	45.0	45.5	45.8	45.5
15	46.1	47.1	47.8	47.1	44.7	45.2	45.6	45.2
16	45.3	46.4	47.2	46.5	44.1	44.6	45.0	44.7
17	43.7	45.2	46.0	45.2	42.8	43.6	44.0	43.6
18	43.7	45.1	46.0	45.1	42.8	43.5	43.9	43.5
19	43.7	45.2	46.0	45.2	42.8	43.6	43.9	43.6
20	Not required				Not required			
21	Not required				Not required			

Table 12 – Maximum Combined Magnetic Field Intensity

2.7.9 Bundled Configuration – Cables Buried 5.0m, 10.0 and 12.0m Deep

The cable depths at the three markers are as follows:

- Marker 2: 5.0m
- Marker 20: 12.0m

- Marker 21: 10.0m

Marker	Maximum Intensities at Different Circuit Angles [µT]							
	Seabed Level				1.0m Above Seabed			
	0°	45°	90°	-45°	0°	45°	90°	-45°
2	46.7	46.7	46.7	46.8	46.6	46.6	46.6	46.6
20	42.3	42.3	42.3	42.3	42.3	42.3	42.3	42.3
21	42.3	42.3	42.3	42.4	42.3	42.3	42.3	42.3

Table 13 – Maximum Combined Magnetic Field Intensity

2.7.10 Calculation Results Spreadsheets and Charts

Spreadsheets containing calculation results and charts have been produced for each of the 21 marker locations.

The spreadsheets were provided to Sun Cable via a DropBox link on 04 May 2022. They are set to open 'read only' by default but this can be overridden by the user if required.

Each marker has its own folder with the folders being named Marker 01, Marker 02, ………. Marker 21.

In each folder, there are up to six spreadsheets; three for when the cables are spaced with the circuit being at angles of 0°, 45° and 90° and similarly for when the cables are bundled. Results for a circuit angle of -45° (i.e. cables running northwest to southeast) have not been plotted.

The spreadsheets are named to reflect the marker number, whether the cables are bundled or spaced and the circuit angle. The term 'Single' has been used when the cables are spaced as only one cable has been considered. Figure 21 shows the Marker 01 spreadsheets.

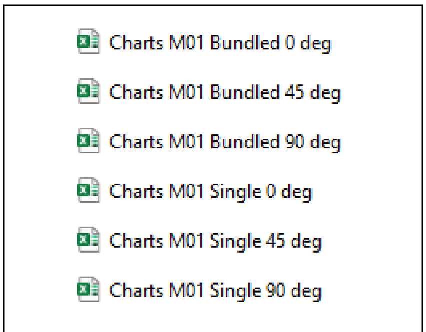

Figure 21 – Marker 01 Spreadsheets

In each spreadsheet the individual sheet tabs are as follows:

- 'Cable' contains the calculation results for the field generated by the cable at different distances above the cable surface.

- 'GM' contains the geomagnetic field calculation results.

- 'Combined' contains the calculation results for the combined cable and geomagnetic field (note that this is a vector sum so the 'Cable' and 'GM' results cannot just be added together).

- 'C01', 'C02' and 'C03' contain charts showing just the cable field at different depths of burial.
    - Sometimes only 'C01' is present – this is where the range of depths does not require three charts.

- 'CGM01', 'CGM02' and 'CGM03' contain charts showing just the combined cable and GM field at different depths of burial.
    - Sometimes only 'CGM01' is present – this is where the range of depths does not require three charts.

- 'GM01; contains a chart showing the GM field.

- 'Co-ordinates' contains information that is used to label the charts.

2.8 Induced Electric Field

As is mentioned in Section 2.1, when something such as seawater or marine life moves through a magnetic field an electric field is induced in the object.

For seawater, the induced electric field can be calculated by multiplying the magnetic field intensity by the velocity of the water. This is the method used by the UK's National Grid company for their Basslink, BritNed, Western Link and Viking HVDC interconnectors[5].

Using the results given in Table 7 as an example (where the configuration is spaced and the burial depth is 1.0m), the maximum cable and GM combined magnetic field intensities at Marker 1 at circuit angles of 0°, 45° and 90° are shown in Table 14 along with induced electric field intensities at different seawater velocities.

1m above seabed level						
Cable Circuit Angle [°]	Maximum Magnetic Field Intensity [µT]	Induced Electric Field Intensity [µV/m] at different Seawater Currents				
		1.0 knot	2.0 knots	3.0 knot	4.0 knot	5.0 knot
		0.5 m/s	1.0 m/s	1.5 m/s	2.1 m/s	2.6 m/s
0	193.9	99.8	199.5	299.3	399.1	498.9
45	216.9	111.6	223.2	334.8	446.4	558.0
90	226.4	116.5	233.0	349.4	465.9	582.4

Table 14 – Induced Electric Field Intensities

The field intensity is at its highest when the cables are lying directly on the seabed surface, see Table 6. The maximum intensity is 4,885.8 µT (see Markers 17, 18 and 19). I have rounded this figure up 4,890µT and the resulting induced electric field intensities are shown in Table 15.

Maximum Magnetic Field Intensity [µT]	Induced Electric Field Intensity [µV/m] at different Seawater Currents				
	1.0 knot	2.0 knots	3.0 knot	4.0 knot	5.0 knot
	0.5 m/s	1.0 m/s	1.5 m/s	2.1 m/s	2.6 m/s
4,890	2,445	4,890	7,335	10,269	12,714

Table 15 – Highest Induced Electric Field Intensities

3 Effects of Electromagnetic Fields on People and Sealife

3.1 Effects on People – Static Magnetic Fields

The International Commission on Non-Ionizing Radiation Protection (**ICNIRP**) is an internationally recognized body that sets guidelines for protection against adverse health effects of non-ionizing radiation.

For static magnetic fields (i.e. those with a frequency of zero Hertz as is the case for the magnetic fields generated by the AAPowerLink cables considered in this study[b]), ICNIRP publishes guidelines for limiting exposure[6]. Table 2 from the guidelines is shown below in Figure 22.

[b] It should be remembered that alternating and high frequency fields that result from harmonic currents and fast moving transients are not covered in this study.

Table 2. Limits of exposure[a] to static magnetic fields.

Exposure characteristics	Magnetic flux density
Occupational[b]	
Exposure of head and of trunk	2 T
Exposure of limbs[c]	8 T
General public[d]	
Exposure of any part of the body	400 mT

[a] ICNIRP recommends that these limits should be viewed operationally as spatial peak exposure limits.
[b] For specific work applications, exposure up to 8 T can be justified, if the environment is controlled and appropriate work practices are implemented to control movement-induced effects.
[c] Not enough information is available on which to base exposure limits beyond 8 T.
[d] Because of potential indirect adverse effects, ICNIRP recognizes that practical policies need to be implemented to prevent inadvertent harmful exposure of persons with implanted electronic medical devices and implants containing ferromagnetic material, and dangers from flying objects, which can lead to much lower restriction levels such as 0.5 mT.

Figure 22 – ICNIRP Magnetic Field Exposure Guidelines

In Figure 22, units of T (Tesla) and mT (milli Tesla) are used. There are 1,000mT in 1T so the general public exposure limit of 400mT can be rewritten as 0.4T.

For the magnetic field calculations that have been performed in this study, units of µT (micro Tesla) have been used. 400mT is equal to 400,000µT.

The magnetic field intensity is at its highest when the cables are lying directly on the seabed surface, see Table 6. Rounding up the values in the table to a maximum of 4,890µT, the general public limit is over 80 times this value.

3.2 Effects on People – Induced Electric Fields

When a person moves through a static magnetic field, see Section 3.1 above, an electric field is induced in that person.

ICNIRP guidelines for induced electric field exposure[7] indicate that peripheral nerve stimulation, vertigo and nausea are the main concerns for people. The guideline requirements and some explanatory text are included in ICNIRP's induced electric field factsheet[8] and are copied in Figure 23 to Figure 25 below.

Basic restrictions

In order to prevent vertigo arising from relatively slow motions in a static magnetic field, the change of the magnetic flux density ΔB should not exceed 2 T during any 3 s period.

For specific work applications, exposure to a static magnetic field up to 8 T can be justified, if appropriate work practices are implemented to control movement-induced sensory effects (controlled conditions)

In the case of a stationary body in a time-varying magnetic field, the peak-to-peak value of the magnetic flux density is equivalent to ΔB and consequently should be limited to 2 T.

Vertigo and resulting nausea may be annoying and disturbing, but they do not indicate a serious long-term health effect. Therefore, no additional reduction factor has been applied to their threshold.

In order to prevent peripheral nerve stimulation (PNS) arising from fast transient motions, the peak internal electric field should not exceed 1.1 V/m.
Because the stimulation of peripheral nerves is regarded as an adverse health effect the reduction factor 5 has been applied to the threshold to account for biological uncertainties.

Figure 23 – ICNIRP Induced Electric Field Exposure Guidelines – Basic Restrictions

Reference levels

A practical way for determining compliance with the basic restrictions for fast transient motions is to ensure that the magnetic flux density does not exceed the reference levels derived conservatively from the basic restrictions.

In order to avoid electrical stimulation of peripheral nerves, the reference level for peak dB/dt, i.e. the time derivative of the magnetic flux density, has been set to 2.7 Ts-1. Note that to account for uncertainties arising from the conversion of the basic restriction to the reference level a reduction factor of approximately 3 is included in this reference level.

Figure 24 – ICNIRP Induced Electric Field Exposure Guidelines – Reference Levels

	Basic restrictions				Reference levels	
Frequency (Hz)	ΔB (T) [1)]	$B_{peak\ to\ peak}$ (T)	Internal electric field strength (Vm^{-1} (peak))		dB/dt (Ts^{-1} (peak))	
Critical effect	Vertigo due to movement in static B field	Vertigo due to time-varying B field	PNS effects due to movement in static B field and due to time-varying B field	Phosphenes due to movement in static B field and due to time-varying B field	PNS effects due to movement in static B field and due to time-varying B field	Phosphenes due to movement in static B field and due to time-varying B field
Exposure condition [2)]	uncontrolled	uncontrolled	Controlled	Uncontrolled	Controlled	Uncontrolled
0	2					
0-1		2				
0-0.66			1.1	1.1	2.7	2.7
0.66-1 [3)]			1.1	0.7/f	2.7	1.8/f

Figure 25 – ICNIRP Induced Electric Field Exposure Guidelines Basic Restrictions Table

One of the key factors is the rate of change of the induced electric field. The guidelines talk about a rapid movement of the head but a rapid change in the cable current could, presumably, cause a similar effect.

Given the safety margin of ≈1,000 that has been shown for static magnetic fields, we do not anticipate the electric field guidelines will be breached for the static condition. However, it is recommended that system fault conditions (where rapid changes in electric current can occur) and the effect of high frequency transient voltages should be investigated as a separate exercise.

3.3 Effects on Sealife

The December 2021 Environment Update[9] issued by the International Cable Protection Committee gives a good overview of interactions between subsea cables and the marine environment.

An extract from the section that deals with electromagnetic fields is shown in Figure 26.

Until recently, knowledge of EMFs on sensitive marine biota was limited. This situation partly reflected a dearth of real-world field studies. Uncertainty was compounded by complexities associated with the different responses of various marine organisms to EMFs that themselves varied as a function of (i) cable voltage, (ii) AC or DC systems, (iii) depth of cable burial, (iv) cable orientation and other factors. However, at least three major reviews (Normandeau et al., 2011; Copping et al., 2016; Albert et al., 2020) and several field studies (Sherwood et al., 2016; Kuhnz et al., 2015; Andrulewicz et al., 2003) have been completed that provide a more informed perspective. The common finding of this research is that there is a lack of evidence for positive or negative effects of cable EMFs on the species studied.

Figure 26 – ICPC Environment Update Extract, Electromagnetic Fields

In the above extract, the term 'biota' means the flora and fauna of a region.

The Environment Update provides a list of 37 references and these are shown in Figure 45 to Figure 47 in Appendix 4.

The Environment Update considers the thermal and other impacts as well as the electromagnetic impact.

AAPowerLink has taken the ICPC's findings into account in its Environmental Impact Statement for the Australian section of the project. An extract is shown below in Figure 27.

Electromagnetic Fields

The operating High Voltage Direct Current (HVDC) Subsea Cable System will generate EMF. The physical effects of EMF on the marine environment are very localised (confined to within a few metres of the cable). Many marine species – from rays and sharks to molluscs and crustaceans – are known to be sensitive to EMF because they use electromagnetic fields for orientation, migration and/or prey detection. It is possible that the EMF generated by the Subsea Cable System could negatively impact the behavioural ecology of some marine species through:

- Effects on predator/prey interactions
- Avoidance/attraction and other behavioural effects
- Effects on species navigation/orientation capabilities
- Physiological and developmental effects (Taormina et al. 2018).

ICPC (2021) reviewed studies of EMF impact on marine biota and found that the research undertaken to-date indicates a lack of evidence for positive or negative effects of cable EMF on the species studied, with studies finding no change in biological assemblages along energised cables. Consequently, as for the potential heat effect discussed above, it is reasonable to conclude that any potential impact of EMF on marine biota will be very localised.

Figure 27 – Extract from AAPowerLink's EIS for Australia.

4 Thermal Calculations

4.1 General

Thermal calculations have been performed for the following situations:

- Cables are buried in the seabed. Temperatures within the seabed material surrounding the cables have been calculated. Finite element calculations using QuickField were performed.

- Cables are sitting on the seabed surface. Cable surface temperatures have been calculated. Analytical calculations and QuickField calculations (but using an analytically calculated heat transfer function) were performed.

For the spaced configuration, there is no thermal interaction between the cables given the minimum spacing is 50m so one single cable on its own has been considered. The cable current is 1,950A.

For the bundled configuration, both cables have been considered and the current in each cable is 683A.

The cable build offered by Prysmian in v02 of their proposal dated 06 July 2020 has been used. This is the cable build that was used in the cable system temperature study and full details of the build are in CCI report ER1203[10].

A cross-section of the cable is shown in Figure 28 and dimensions and thermal properties are shown in Table 16.

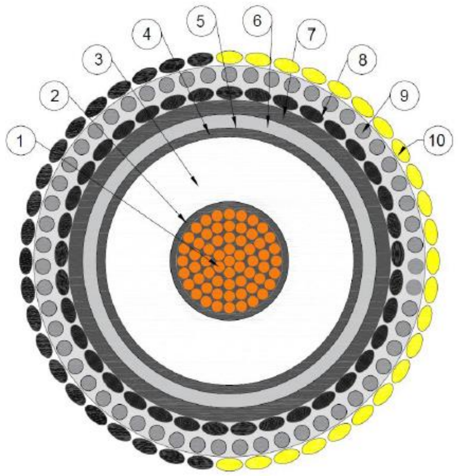

Figure 28 – Prysmian Cable Build

#	Component	Nominal Thickness [mm]	Nominal Diameter [mm]	Material	TR [Km/W]
1	Conductor	-----	60.0	Copper	---
2	Conductor Screen	2.0	64.0	Semi-conducting LXLPE	3.5
3	Insulation	26.0	116.0	LXLPE	3.5
4	Insulation Screen	1.8	119.6	Semi-conducting LXLPE	3.5
5	Water Blocking	0.6	120.8	Semi-conducting swellable tape	3.5
6	Lead Alloy Sheath	3.3	127.4	Lead alloy	---
7	Polyethylene Sheath	3.3	134.0	High density polyethylene	3.5
8	Armour Bedding	2.0	138.0	Polypropylene strings	6.0
9	Armour	6.0	150.0	Steel flooded with bitumen	---
10	Serving	5.5	161.0	Polypropylene strings	6.0

Table 16 – Prysmian Cable Build

Prysmian do not give all the key cable dimensions in their proposal. Those given by Prysmian are shown in green text in Table 16 and the dimensions shown in black text have been estimated by CCI.

4.2 Cables Buried in the Seabed

The calculations assume the convention in the internationally recognized IEC standard IEC 60287[11] where the ground (or seabed in the case of AAPowerLink) surface temperature is assumed to be isothermal for thermal calculations. Calculations were performed for a surface temperature of 25°C.

The seabed material thermal resistivity was taken to be 1.2Km/W.

The surface temperature and thermal resistivity are those at Murrumujuk and Shoal Bay (**M & SB**), see Figure 44 in Appendix A. The inputs were selected as, apart from in the very short Ular Landing section in Singapore, they result in the highest cable temperatures for any given cable current and burial depth.

4.2.1 Spaced Configuration

At a depth of burial of 0.5m to the top of the cable and a cable current of 1,950A, the conductor temperature is 57.1°C[c].

Figure 29 shows the temperature distribution within the seabed material surrounding the cable.

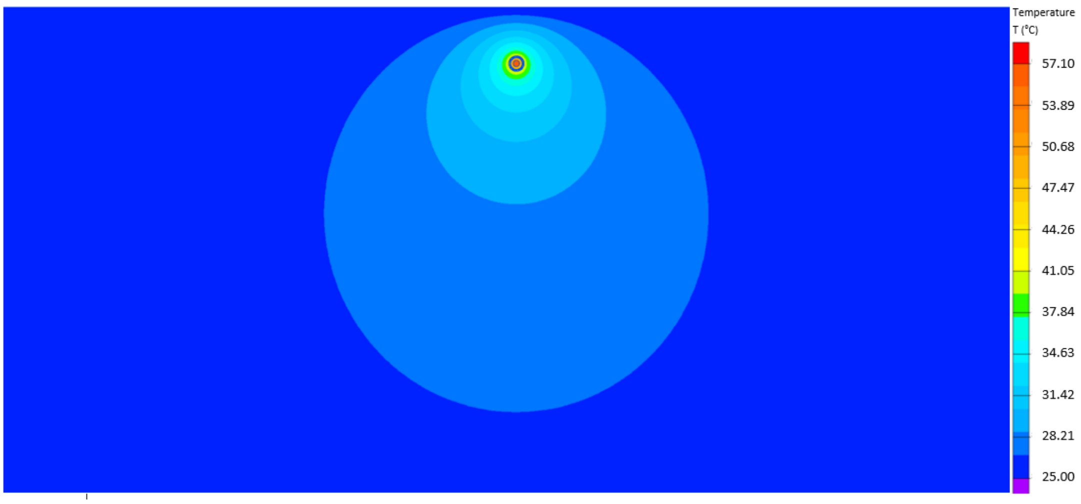

Figure 29 – M & SB, 0.5m Depth of Cover, Spaced (picture extent ±5m wide, 5m deep)

Figure 30 shows a zoomed in view of Figure 29.

[c] This is the temperature calculated by QuickField. An analytical check calculation agreed to within 0.1°C.

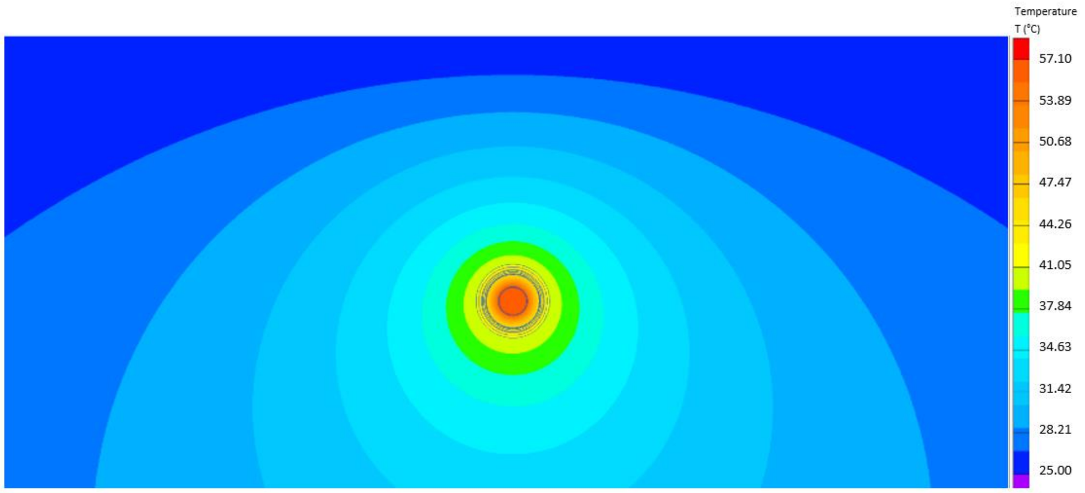

Figure 30 – M & SB, 0.5m Depth of Cover, Spaced (picture extent ±1m wide, 1m deep)

In Figure 31, isotherms (lines of equal temperature) have been added to Figure 30. The surface temperatures is 25°C and the isotherms are 1°C apart so the first isotherm down from the surface is 26°C, the second is 27°C and so on.

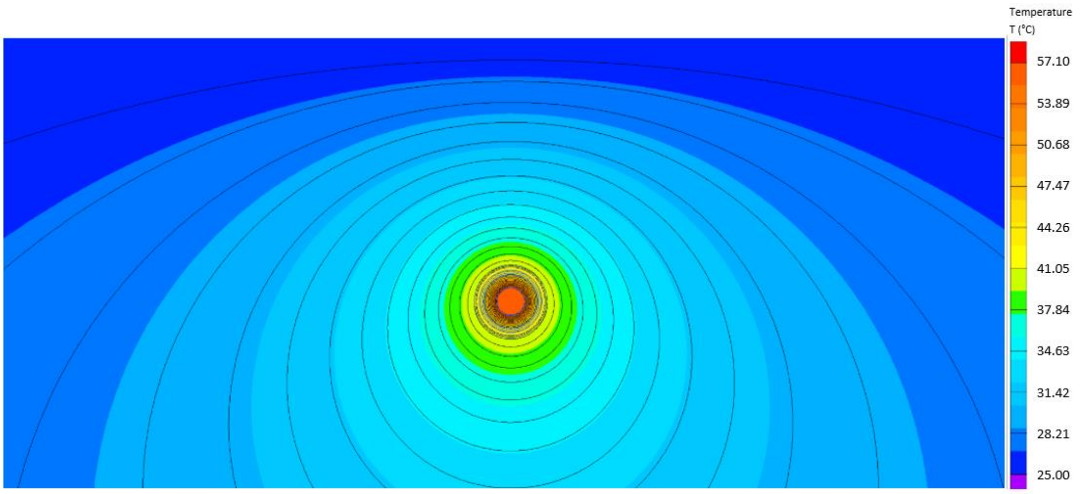

Figure 31 – M & SB, 0.5m Depth of Cover, Isotherms (picture extent ±1m wide, 1m deep)

Figure 32 shows the vertical temperature profile immediately above the cable moving down from the seabed surface. The temperature starts at 25°C at the seabed surface and increases to about 40.5°C at the cable surface.

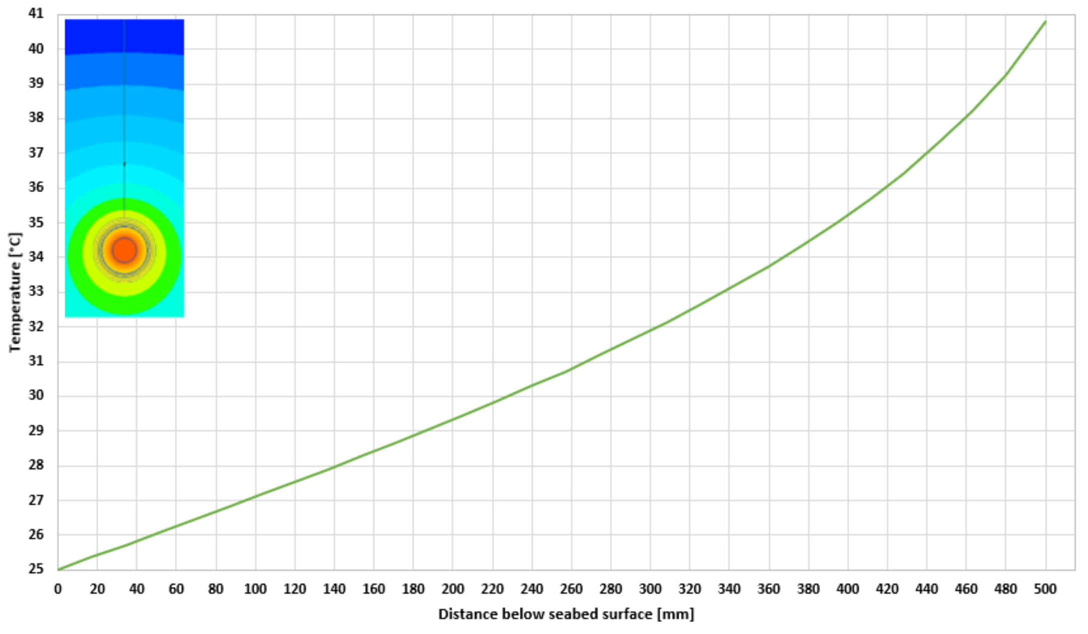

Figure 32 – M & SB, 0.5m Depth of Cover, Spaced, Vertical Temperature Profile

If the depth of cover is increased to 1.0m, the cable conductor temperature increases to 61.4°C at a cable current 1,950A.

Temperature distributions are shown in Figure 33 and Figure 34.

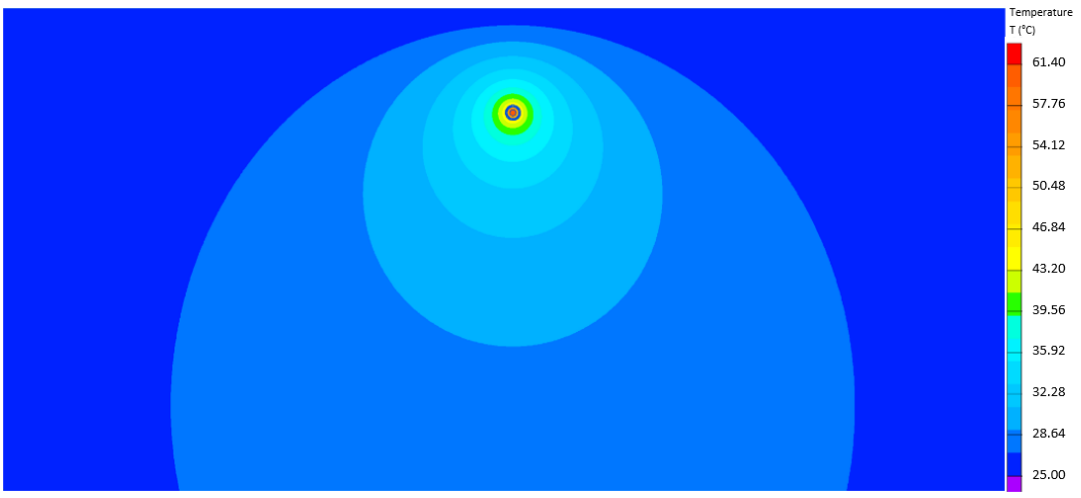

Figure 33 – M & SB, 1.0m Depth of Cover, Spaced (picture extent ±5m wide, 5m deep)

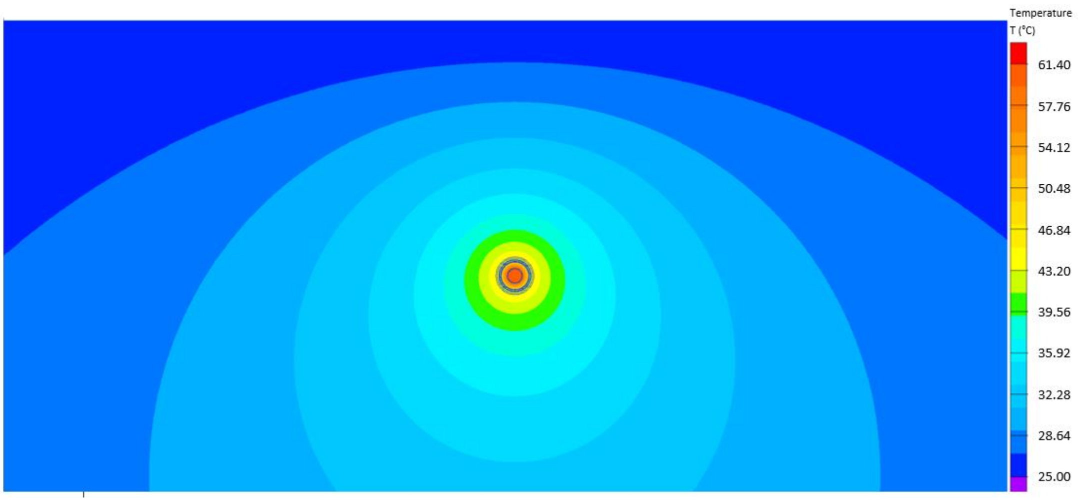

Figure 34 – M & SB, 1.0m Depth of Cover, Spaced (picture extent ±2m wide, 2m deep)

In Figure 35, the isotherms are spaced 1°C as before.

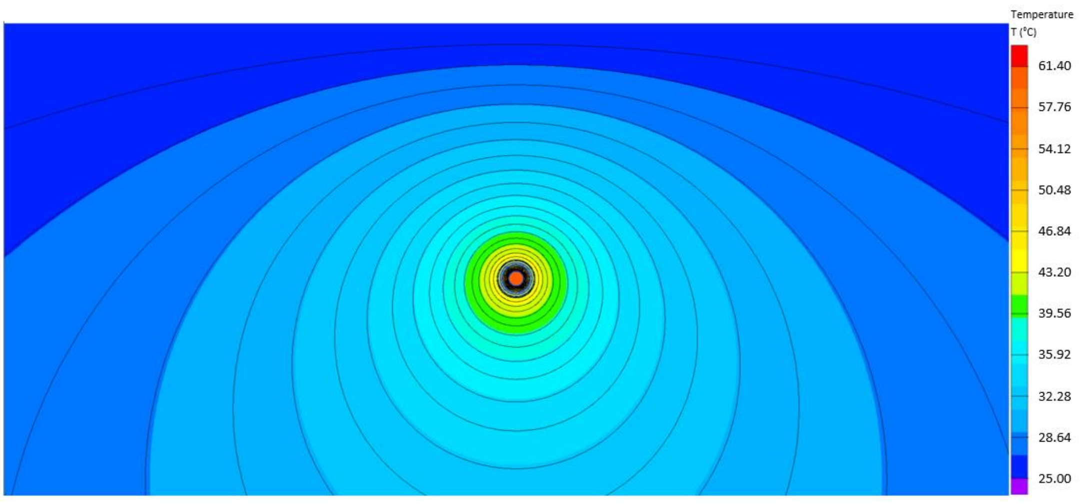

Figure 35 – M & SB, 1.0m Depth of Cover, Isotherms (picture extent ±2m wide, 2m deep)

Figure 36 shows the vertical temperature profile immediately above the cable moving down from the seabed surface. The temperature starts at 25°C at the seabed surface and increases to about 44.5°C at the cable surface.

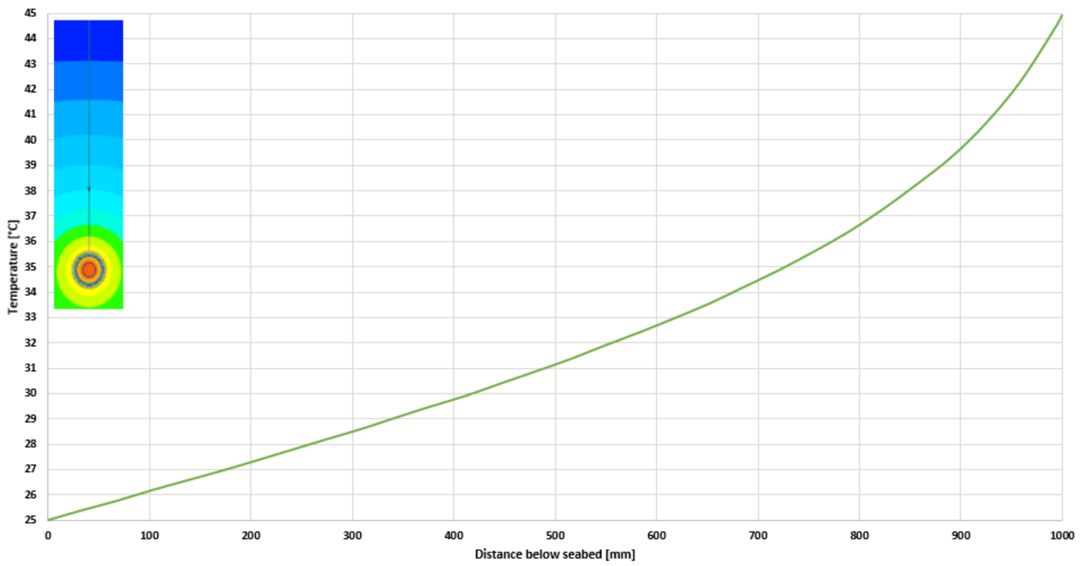

Figure 36 – M & SB, 1.0m Depth of Cover, Spaced, Vertical Temperature Profile

If the depth of cover is increased to 2.5m, the cable conductor temperature increases to 67.9°C at a cable current 1,950A.

Figure 37 shows the vertical temperature profile immediately above the cable moving down from the seabed surface. The temperature starts at 25°C at the seabed surface and increases to about 51.0°C at the cable surface.

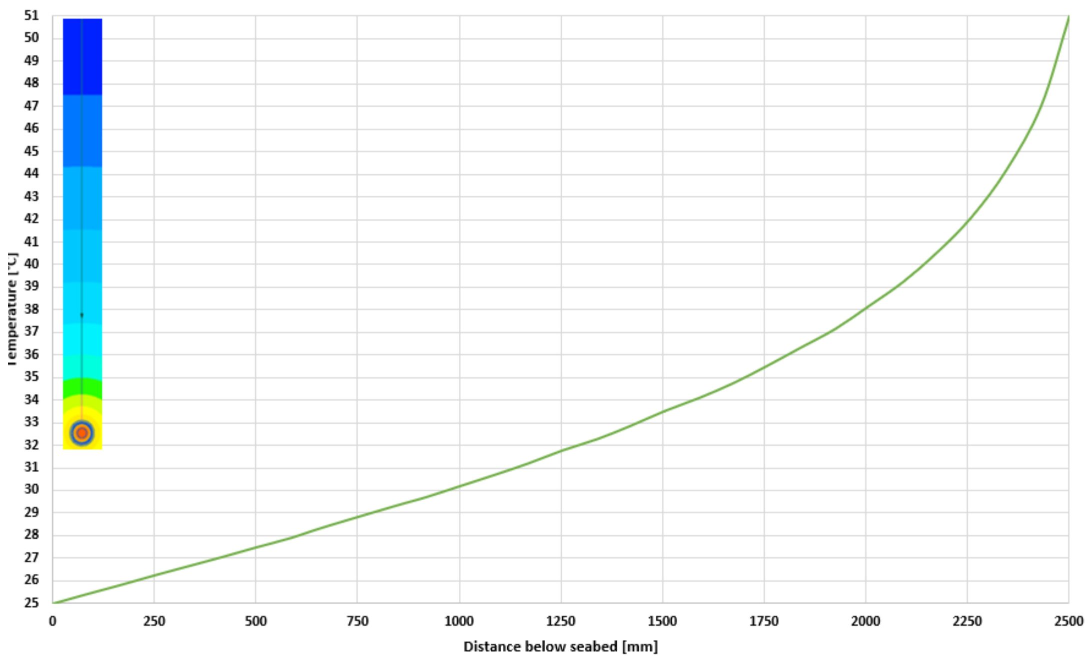

Figure 37 – M & SB, 2.5m Depth of Cover, Spaced, Vertical Temperature Profile

Table 17 shows an analysis of the temperature profiles in Figure 32, Figure 36 and Figure 37.

Burial Depth to Top of Cable [m]	Depth where Temperature is 26°C [mm]	Temperature at 100mm below Surface [°C]
0.5	48	27.2
1.0	90	26.2
2.5	200	25.4

Table 17 – Seabed Material Temperatures

4.2.2 Bundled Configuration

From Section 4.2.1, it is clear that the lower the burial depth, the greater is the impact of the cable on temperatures close to the seabed surface. Given this, only a burial depth of 0.5m has been considered for the bundled configuration.

The current in each cable is 683A so less heat is generated than in the spaced configuration where the current is 1,950A.

The conductor temperature is 29.8°C.

Figure 38 shows the temperature distribution.

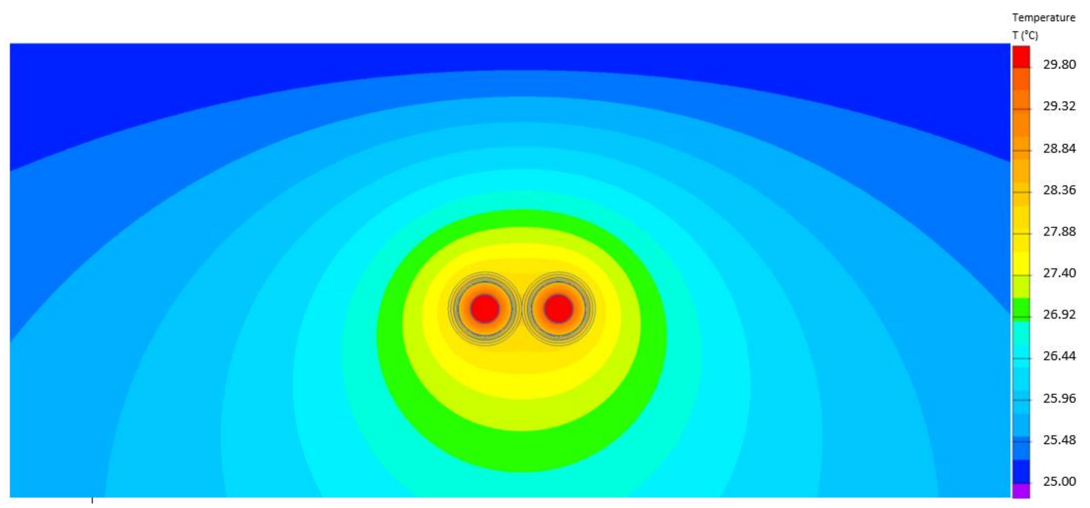

Figure 38 – M & SB 0.5m Depth of Cover, Bundled (picture extent ±1m wide, 1m deep)

Isotherms have been added to the Figure 38 temperature distribution and are shown in Figure 39. As for the spaced configuration, the isotherms are spaced 1°C apart.

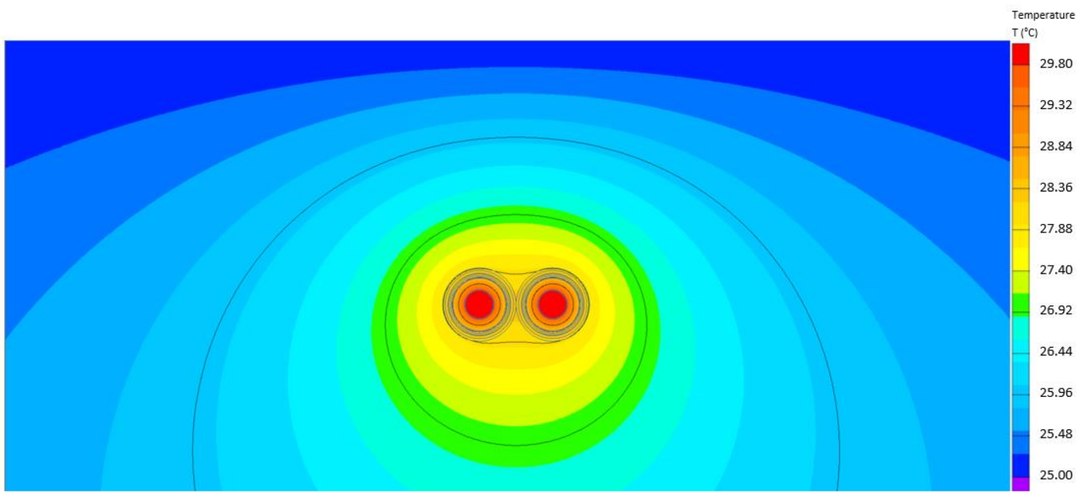

Figure 39 – M & SB 0.5m Depth of Cover, Bundled (picture extent ±1m wide, 1m deep)

Figure 40 shows the vertical temperature profile immediately above the cable moving down from the seabed surface. The temperature starts at 25°C at the seabed surface and increases to about 27.9°C at the cable surface.

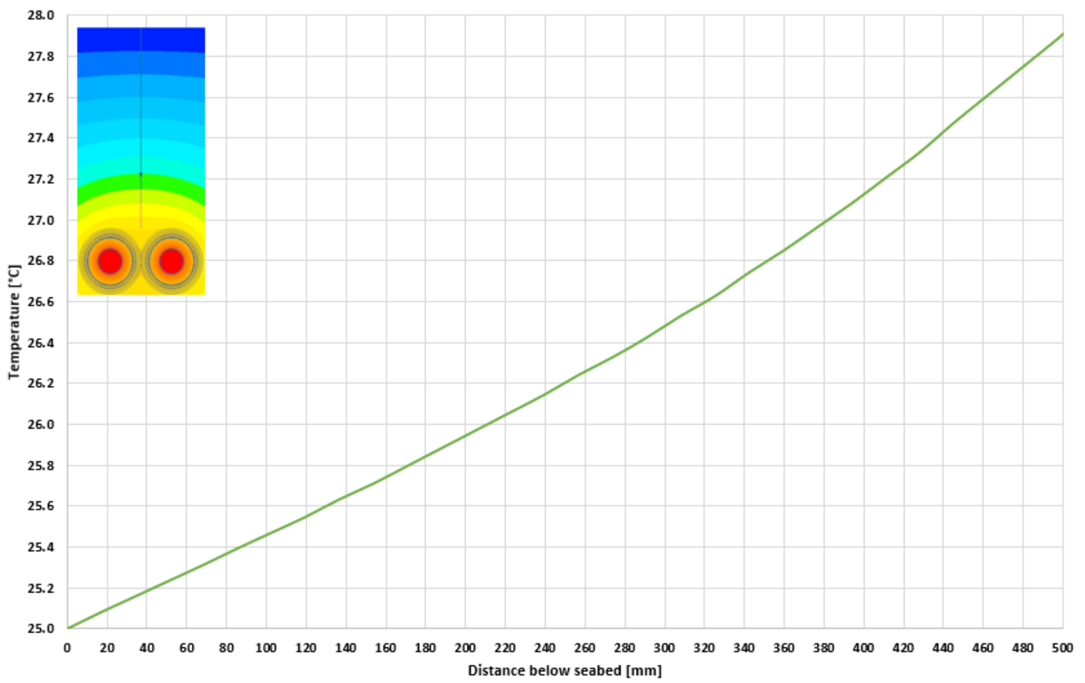

Figure 40 – M & SB, 0.5m Depth of Cover, Bundled, Vertical Temperature Profile

In Figure 40, the depth where temperature is 26°C is 210mm and the temperature 100mm below the surface is just under 25.5°C.

4.3 Cables on the Seabed Surface

When a cable is sitting on the seabed surface, heat transfer from the cable is by conduction, natural convection (caused by the heat generated by the cable), forced convection (caused by the natural movement of seawater) and radiation.

Calculating and applying representative heat transfer functions is difficult and there is no internationally accepted method of calculation. CIGRE Technical Brochure 640[12], which is a guide for current rating calculation methods, sidesteps the issue and argues that cables on the seabed surface will eventually be covered with sediment and suggests a burial depth of 0.3m should be used in calculations.

We have performed some preliminary calculations assuming there is no sediment cover and the worst case is that the cable surface temperature will be around 2 to 3°C above the ambient sea temperature.

5 Cable Crossing Effective Thermal Resistivity

The scope of work requirement is for the increase in thermal resistance as a result of the presence of cable crossing structures, such as mattresses or similar, to be calculated.

Full thermal calculations that determine the thermal interaction between the AAPowerLink cables and the crossed asset are not required.

At this stage, crossing structure designs and thermal properties are not known so we used a generic approach and considered how external thermal resistance (i.e. T4 in IEC 60287) varies for different values of crossing material thermal resistivity.

The work was performed using QuickField finite element modelling software.

The crossing structure was assumed to be solid with the only heat transfer mode being conduction. This should be a worst case.

Based on our experience, we assumed a crossing structure thickness of 0.5m and a width of 32m.

A part of the QuickField model after the modelling mesh had been created is shown in Figure 41.

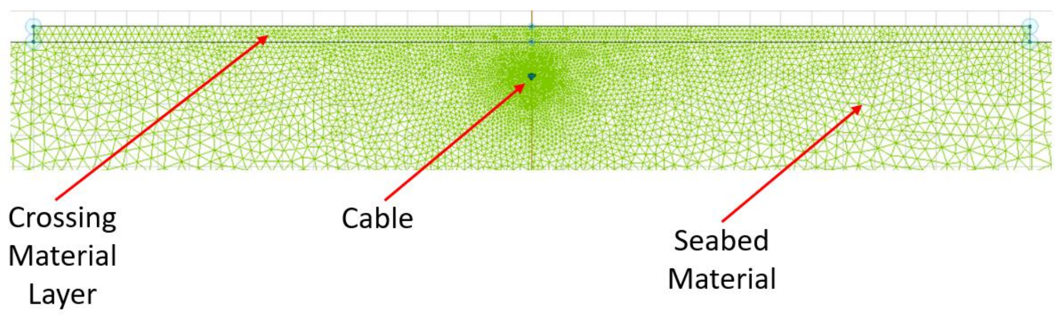

Figure 41 – Model part view after mesh creation

Modelling results are shown in Figure 42.

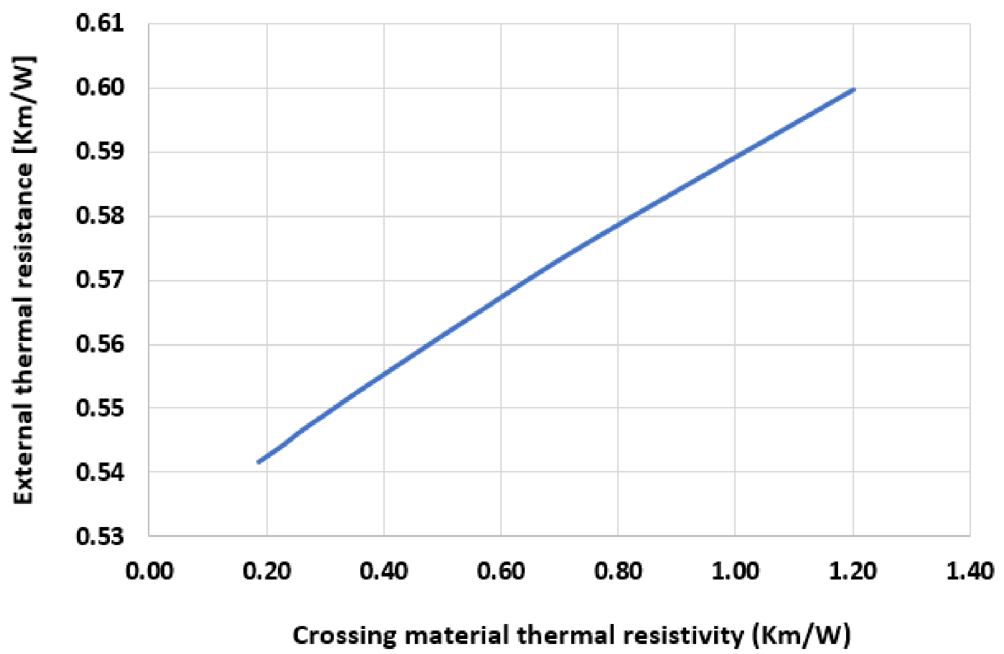

Figure 42 – Thermal resistance sensitivity results

From Figure 42, it can be seen that there is only a relatively small change in external thermal resistance (~0.54Km/W to ~0.60Km/W) as the crossing material thermal resistivity increases from ~0.2Km/W to 1.20Km/W.

Our experience with cable crossings is that different asset owners have different requirements for crossing structures. Two examples, a lattice type concrete mattress and a rock berm, are shown in Figure 43.

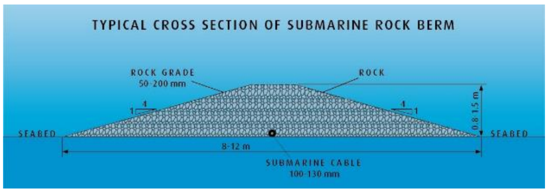

Figure 43 – Typical crossing materials

To give an indication of thermal resistivities that can be expected, concrete is typically in the range 0.6Km/W to 1.0Km/W and rock is typically between 0.2Km/W and 0.5Km/W (but it can be higher). The gaps between the concrete cells and rocks will fill with sand or similar so a composite value of thermal resistivity needs to be calculated. A recent example from a project in Scotland is that a composite value of 0.67Km/W was calculated.

When detailed thermal interaction calculations are performed for individual crossings, we suggest that calculations should assume heat transfer by conduction only in the first instance. Thereafter convection could be included to either improve the thermal rating of the cables involved in the crossing or to optimise the crossing design.

Appendix 1 – Environmental Conditions

	ML	SB	ESW	ACS	DW	SW	S	SNC	U	UL
Section No.	1	2	3	4	5	6	7	8	9	10
Length [km]	5	60	27	485	700	2,900	43.5	6	0.5	0.1
Burial depth [m]	2.0	0.5	5.0	0.5	0.0	1.0	2.0	12.0	10.0	1.5
Spacing [m]	Pole 1 + MR bundled Pole 2 min. 50m away				Pole 1, MR, Pole 2 individually laid. Min 50m spacing between each cable	Pole 1 + MR bundled Pole 2 min. 50m away			HDD Min 5m spacing between each duct	Direct Buried Min 2m Spacing
Soil temp [°C]	25	25	25	20	8	18	25	20	20	30
Soil thermal resistivity [Km/W]	1.2	1.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.2
Max water depth [m]	10	20	50	100	1,800	40	40	40	10	---

Figure 44 – Environmental Conditions

The above table is a copy of the table in Section 2.4.3 of Rev 3 of the Cable Temperature Study Report, ER1203.

Appendix 2 – Marker 1 to 21 GM Field Intensities and Components

Marker	Water Depth [m]	Longitude [Decimal Degrees]	Latitude [Decimal Degrees]	Declination (+ E | - W) [°]	Inclination (+ D | - U) [°]	Horizontal Intensity [nT]	North Component (+ N | - S) [nT]	East Component (+ E | - W) [nT]	Vertical Component (+ D | - U) [nT]	Total Intensity [nT]
1	-12	12.27795155 S	130.75341392 E	2.1333	-39.2485	35,745.40	35,720.60	1,330.60	-29,203.70	46,158.30
2	-26	12.27299949 S	130.49877964 E	2.0873	-39.2375	35,762.40	35,738.60	1,302.50	-29,206.10	46,172.90
3	-68	11.96621221 S	129.38326808 E	1.8603	-38.7134	35,941.70	35,922.80	1,166.80	-28,808.50	46,062.30
4	-123	11.88296104 S	127.39944085 E	1.5625	-38.5369	36,089.30	36,075.90	984.00	-28,744.60	46,137.80
5	-114	12.04020878 S	124.99650192 E	1.3070	-38.7629	36,158.60	36,149.20	824.80	-29,033.70	46,372.40
6	-800	11.34901370 S	122.69093277 E	1.0567	-37.5573	36,555.10	36,548.90	674.10	-28,107.80	46,112.10
7	-500	11.00510552 S	121.23696748 E	0.9494	-36.9583	36,749.50	36,744.50	608.90	-27,650.80	45,990.20
8	-150	9.89100520 S	119.68758045 E	0.8088	-34.9806	37,236.30	37,232.60	525.60	-26,054.30	45,446.40
9	-600	9.08201691 S	117.51746456 E	0.7232	-33.5490	37,635.00	37,632.00	475.00	-24,956.30	45,157.60
10	-30	9.04794443 S	116.78992167 E	0.7188	-33.5187	37,663.20	37,660.20	472.50	-24,946.40	45,175.70
11	-160	8.97427178 S	116.23598368 E	0.7141	-33.4102	37,712.20	37,709.20	470.00	-24,876.30	45,177.80
12	-100	8.54566780 S	115.87509086 E	0.6891	-32.6213	37,882.20	37,879.50	455.60	-24,246.50	44,977.30
13	-400	7.02348357 S	116.52614970 E	0.5789	-29.6466	38,389.00	38,387.10	387.90	-21,849.30	44,171.40
14	-75	6.18062839 S	114.88118866 E	0.5439	-28.0612	38,729.40	38,727.70	367.60	-20,645.90	43,888.70
15	-50	4.85746312 S	110.25726466 E	0.5202	-25.7904	39,328.20	39,326.60	357.10	-19,003.90	43,679.00
16	-35	2.92824866 S	107.30347484 E	0.3831	-22.0799	40,004.70	40,003.80	267.50	-16,227.90	43,170.80

Marker	Water Depth [m]	Longitude [Decimal Degrees]	Latitude [Decimal Degrees]	Declination (+ E | - W) [°]	Inclination (+ D | - U) [°]	Horizontal Intensity [nT]	North Component (+ N | - S) [nT]	East Component (+ E | - W) [nT]	Vertical Component (+ D | - U) [nT]	Total Intensity [nT]
17	-22	1.08912774 N	104.2014475 E	0.0505	-13.4677	41,081.10	41,081.10	36.20	-9,838.20	42,242.70
18	-45	1.23343793 N	104.0569201 E	0.0355	-13.1513	41,114.80	41,114.80	25.50	-9,606.60	42,222.20
19	-35	1.20306415 N	103.8557594 E	0.0279	-13.2492	41,117.40	41,117.40	20.00	-9,681.30	42,241.80
20	-15	1.24169173 N	103.70427100 E	0.0182	-13.1797	41,130.50	41,130.50	13.10	-9,631.70	42,243.20
21	-33	1.22181042 N	103.78827375 E	0.0235	-13.2147	41,123.70	41,123.70	16.90	-9,656.60	42,242.30

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