Understanding the effects of electromagnetic field emissions from Marine Renewable Energy Devices (MREDs) on the commercially important edible crab, Cancer pagurus (L.)

Understanding the effects of electromagnetic field emissions from Marine Renewable Energy Devices (MREDs) on the commercially important edible crab, *Cancer pagurus* (L.)

Kevin Scott [a, b], Petra Harsanyi [a], Alastair R. Lyndon [b].

[a] St Abbs Marine Station, The Harbour, St Abbs, Scotland, UK, TD14 5PW

[b] Centre for Marine Biodiversity & Biotechnology, John Muir Building, Heriot Watt University, Edinburgh, Scotland, UK, EH14 4AS.

Corresponding author: Kevin Scott
Email: kevin.scott@marinestation.co.uk
Tel: +(44) 1890771688

Email addresses:

Kevin Scott: kevin.scott@marinestation.co.uk

Petra Harsanyi: petra.harsanyi@marinestation.co.uk

Alastair Lyndon: A.R.Lyndon@hw.ac.uk

Key Words: *Cancer pagurus*; edible crab; electromagnetic field; environmental stressor; marine renewable energy.

Conflicts of interest: none.

Contributions: All research was designed and conducted by Kevin Scott and Petra Harsanyi with regular input from Alastair Lyndon. All three authors contributed to the article preparation.

Funding: All work was carried out at St Abbs Marine Station and Heriot Watt University with funding obtained from the Nesbitt-Cleland Trust. Consumables were funded through St Abbs Marine Station.

Abstract

The effects of simulated electromagnetic fields (EMF), emitted from sub-sea power cables, on the commercially important decapod, edible crab (*Cancer pagurus*), were assessed. Stress related parameters were measured (L-Lactate, D-Glucose, Haemocyanin and respiration rate) along with behavioural and response parameters (antennular flicking, activity level, attraction/avoidance, shelter preference and time spent resting/roaming) during 24-hours. Exposure to EMF had no effect on Haemocyanin concentrations, respiration rate, activity level or antennular flicking rate. EMF exposure significantly disrupted haemolymph L-Lactate and D-Glucose natural circadian rhythms. Crabs showed a clear attraction to EMF exposed shelter (69%) compared to control shelter (9%) and significantly reduced their time spent roaming by 21%. Consequently, EMF emitted from Marine Renewable Energy Devices (MREDs) will likely affect edible crabs both behaviourally and physiologically, suggesting that the impact of EMF on crustaceans must be considered when planning MREDs.

1. Introduction

The predicted decline in non-renewable energy sources in future decades (Pimentel *et al.* 2002) indicates the need for alternative renewable energy sources. Due to reduced planning constraints, lack of inexpensive land near major population centres (Bilgili *et al.* 2011), and perceived aesthetic problems with many renewable energy structures (Gill 2005), there is increasing pressure to move potential locations offshore. Wind speeds tend to be significantly higher offshore than onshore thus producing larger amounts of energy per turbine (Bilgili *et al.* 2011). Vast open spaces offshore also help avoid wake effects (shading effect of a turbine on those downwind of it) by allowing turbines to be placed at greater distances apart (Chowdhury *et al.* 2012). As the global energy demand grows, inshore areas are increasingly being utilised by the energy sector looking to increase energy production via wave and tidal energy devices (Frid *et al.* 2012). Therefore, there is a requirement for appropriate assessment of the implications of both offshore and inshore renewable energy generation with regards to current ecological status and potential future consequences (Gill 2005). Currently, the UK is the largest global producer of electricity from offshore wind farms and has more projects in planning or construction than any other country (Smith *et al.* 1999; Crown Estates 2017). Proposed sites and developments are based on current knowledge and assessments of the siting environment, despite relatively little being known about the ecological effects of such developments on marine benthic organisms. Some studies suggest that turbine arrays could increase biodiversity through new habitat provision (Landers *et al.* 2001; Lindeboom *et al.* 2011), whereas detrimental effects of turbine arrays on birds (Garthe and Hüppop, 2004) and fish (Westerberg and Lagenfelt 2008) have also been found. Furthermore, it is feared that marine mammals might be sensitive to minor changes in magnetic fields associated with these developments (Walker *et al.* 2003). There is currently a gap in our knowledge of the effects of these arrays on crustaceans.

Electromagnetic fields (EMF) are associated with Marine Renewable Energy Devices (MREDs). EMFs originate from both anthropogenic (telecommunication cables, power cables, marine renewable energy devices) and natural (Earth's natural geomagnetic field) sources. It has been shown that industry-standard AC cables can be effectively insulated to prevent electric field (E-field) emissions but not magnetic field (B-field) emissions (Gill 2005). Standard cable configurations combined with the existing B-field creates induced electromagnetic fields (iEM fields) (Gill 2005). The magnetic field (B-field) leakage has been shown to be of concern as it will interact with magnetite-based internal compasses in marine organisms (Öhman *et al.* 2007). Electric currents between 850 and 1600 A (Amperes) tend to be found in undersea cables consequently producing an electromagnetic field of around 3.20 millitesla (mT) (1,600A) in a perfect wire (Bochert and Zettler, 2006). As with all electromagnetic fields this quickly diminishes away from the source, with values of around 0.32mT and 0.11mT at 1 metre (m) and 4 m respectively (Bochert and Zettler 2006). In a report by Normandeau *et al.* (2011) there was shown to be a great variation in electromagnetic field strength arising from different structures, cables and current values. In a recent report (Thomsen *et al.* 2015) higher EMF emission values were recorded for export cables compared to inter turbine cables. It was also noted in this report that EMF values recorded were considerably higher around the cables than around the wind turbine bases. An assessment of the literature (COWRIE 2003) highlights that the current state of knowledge on EMF strengths emitted by undersea power cables is insufficient to allow an informed assessment. The European edible crab, *Cancer pagurus* L., is found throughout Western

Europe from Norway to northern France. They are commonly found from the shoreline to offshore depths around 90m. They are a heavily exploited commercial species with the present UK and Ireland annual catch around 34,600 tonnes (Bannister 2009). There is a high probability that this species will encounter sub-sea power cables resulting in increased EMF exposures, potentially leading to stress responses. In crustaceans, haemolymph analysis enables measurement of stress through detection of abnormalities in internal chemical processes. Previous studies (Taylor *et al.* 1997; Durand *et al.* 2000; Bergmann *et al.* 2001; Lorenzon *et al.* 2007) show that L-Lactate and D-Glucose are useful measures of stress in crustaceans, whilst respiration rates in marine organisms are also reliable indicators of certain environmental stressors (Paterson and Spanoghe 1997; Doney *et al.* 2012; Brown *et al.* 2013). It is also known that behavioural and response parameters (attraction/avoidance, antennular flicking rate, and activity level) can be affected by stress (Stoner 2012). The aim of the present paper is to determine the effects of EMFs on edible crabs using a combination of the above stress indicators.

2. Methods and Materials

Intermoult crabs were obtained from local fishermen and the St Abbs and Eyemouth Voluntary Marine Reserve (St Abbs, Berwickshire, UK) for each experiment. Crabs were kept in 1000L flow through tanks with ambient sea temperature and natural photoperiod for a minimum acclimation period of 1 week at densities of no more than 5 crabs per tank. Each crab was sexed, carapace width measured (mm) and a condition assigned using a condition index (Table 1). Crabs were categorized into size classes based on carapace width (10-79mm – small, 80-120mm – medium, 121mm+ - large).

2.1. Physiological Analyses

2.1.1. Haemolymph Analysis

During experimentation four 70L tanks were set up with flow through seawater (UV sterilised and filtered) which was temperature controlled (TECO TK1000) to ambient conditions. Temperature and light intensity was constantly measured via data loggers (Onset HOBO temperature/light pendant). Within each tank a perforated plastic enclosure enabled the crab to be held in position over the magnets. The EMF was produced by placing four electric solenoid magnets (24V) connected to variable power supplies (QW-MS305D) on ceramic tiles underneath the tanks. The magnets were run at full power, thus creating an electromagnetic field (peak 40mT measured by an AlphaLab, Inc Gaussmeter Model GM-2) which covered the experimental area. The experiment was repeated using a lower strength EMF (peak 2.8mT) to correspond with the expected, although highly variable, levels on the surface of a sub-sea power cable and correspond to those in previous studies (Bochert and Zettler, 2006).

Haemolymph samples were collected, within 60 seconds, from the arthrodial membrane at

Index	Description
1 – Perfect	Body intact with no damage, black spot or other visible defects.
2 – Good	One or two legs missing no carapace damage.
3 – Ok	More than two legs missing, limited carapace damage or slight blackspot.
4 – Poor	One or both claws missing, damaged carapace and widespread blackspot.
5 - Bad	Legs and claws missing, extensive carapace damage and/or blackspot.

Table 1 Condition index for *Cancer pagurus*. All crabs used throughout these experiments were grade 1 or 2 (Adapted from Haig *et al.* 2015)

the base of the fifth walking leg using 1ml syringes with 25G needles. Samples of 250µl, 300µl and 700µl were collected from the different size groups respectively. Haemolymph was transferred into 1.5ml cryogenic vials, with 50µl of haemolymph from each sample stored in a separate vial for Haemocyanin analysis. Samples were frozen in liquid Nitrogen and stored in a freezer (-25°C). To obtain baseline data, haemolymph was collected before exposure (0h) then again after 4h, 8h and 24h. All haemolymph collection was staggered with 5 minutes between each sample to ensure time consistency throughout the experiment. For all experiments, sample times were consistent as follows: 0h (09:00), 2h (11:00), 4h (13:00), 6h (15:00), 8h (17:00) and 24h (09:00).

Haemolymph was deproteinated using the procedure of Paterson and Spanoghe (1997). Samples were thawed, vortexed and mixed with an equal volume of chilled 0.6M perchloric acid (BDH 10175). Inactivated proteins were separated by centrifugation at 25,000g for 10 minutes (Eppendorf 5417C, rotor 30 x 1.5-2ml). After neutralizing the supernatant with 3M potassium hydroxide (BDH 29628) the precipitated potassium perchlorate was separated by centrifuging at 25,000g for a further 10 min. The supernatant was then frozen and stored at -25°C.

2.1.1.1. D-Glucose

D-Glucose concentration was measured using a D-Glucose assay kit (Sigma GAGO20-1KT) according to the procedure in Barrento *et al.* (2010). Haemolymph samples were incubated for 30 min at 37°C with an equal part of the assay reagent. 300µl of 12N sulphuric acid (BDH) was added to stop the reaction and the solution added to a 96 well flat-bottomed microplate (Wheaton 712122). The plates were then analysed spectrophotometrically at 540nm (Molecular Devices, Spectramax M5) and D-Glucose concentration calculated using a calibration curve of standards of known concentration.

2.1.1.2. L-Lactate

L-Lactate concentration of deproteinated haemolymph samples were measured using L-Lactate reagent (Trinity Biotech, Wicklow, Ireland no. 735-10), per the procedure described by Barrento *et al.* (2010). Samples of haemolymph (2.8µl) were mixed with L-Lactate reagent (280µl), then incubated for 10 min at room temperature. These were then added into the wells of the 96-well flat-bottom microplate. The plate was then analysed spectrophotometrically at 540nm and L-Lactate concentration was calculated from a calibration curve using standards of known concentration (Trinity Biotech, Wicklow, Ireland L-Lactate standards set no. 735-11).

2.1.1.3. Haemocyanin

Haemocyanin concentrations were determined spectrophotometrically. 50µl of haemolymph was diluted with 2ml chilled distilled water and 280µL added to the wells of the 96-well flat-bottom microplate and the absorbance at 335nm was measured twice. Haemocyanin concentration (mg/ml) was calculated from the molar extinction coefficient $E^{mM}_{1\ cm}$= 17.26 as previously described by Harris and Andrews (2005).

2.1.2. Respiration

Thirty juvenile (≤79mm carapace width) intermoult crabs were collected from the intertidal zone around St Abbs and placed into two 1000L tanks with seawater flow-through. Crabs with a carapace width of over 80mm were too large for the respiration chamber so were discarded. Inside a Helmholtz coil (2.8mT) a 46L flow through tank was set up as a water bath, with filtered, UV sterilised seawater connected to a sump tank and temperature control unit to ensure temperature stability. A 0.3L respiration chamber was filled with UV sterilised filtered seawater and placed into the water bath. The fibre optic probe (Presens polymer optical fibre POF) was attached to the chamber. An optical oxygen meter (Presens Fibox 3) was used to measure oxygen levels using Presens PSt3 (detection limit 15ppb)

sensor spots. This meter was connected to a computer and a blank was run for a period of 30 minutes. To eliminate bacterial respiration from water samples, a blank was run prior to each trial and the information obtained was considered when calculating oxygen consumption of the crabs. The system was calibrated using a conventional two-point oxygen-free and oxygen-saturated system. Oxygen-free water was obtained using Sodium sulphite (Na_2SO_3) to remove any oxygen, whilst oxygen saturation was achieved through bubbling air vigorously into the water sample for a period of 20 minutes, stirring to ensure the water was not supersaturated.

Crabs were randomly selected, weighed and carapace width measured. The crabs were then placed into the respiration chamber and acclimated for 1 hour with the water flow-through valve open. After acclimation, the valve was closed and measurements taken until a limit of 60% air saturation was reached, or for a total of 30 minutes. 15 individuals were ran as control with the Helmholtz coil switched off and 15 were acclimated with no EMF present then subjected to an EMF for the duration of the experiment. The % air saturation was recorded for each individual and converted to oxygen consumption (mg/g/h).

2.1.3. Helmholtz Coil

Two Helmholtz coils were set up with four 12L glass tanks each, situated in a recirculated temperature controlled water bath. Tank sides were covered with netting to reduce visual stimuli. Tanks were kept at 10°C and were constantly aerated with air stones. 10 large male and 10 large female crabs were randomly selected (carapace width 121mm+), weighed and carapace width recorded before being placed into the experimental tanks. After a 1 hour acclimation period, baseline haemolymph samples were taken from each crab (800µL) and one of the Helmholtz coils switched on, with the other acting as a control. Subsequent haemolymph samples were taken at 2, 4 and 6 hours. Haemolymph was sampled using the previously mentioned protocol. After 6 hours, the Helmholtz coil was switched off and the crabs were left overnight. 24 hours after the baseline haemolymph sample was taken another baseline sample was taken and the other Helmholtz coil was switched on and further samples taken at the same times as the previous day. This allowed all crabs to be sampled during exposure to EMF and control conditions and helped to eliminate individual variances by comparing an individual throughout both treatments. The EMF created by the Helmholtz coil was measured and mapped and gave a field strength of 2.8mT uniformly distributed throughout the experimental area. Three additional individual crabs were sampled over the two-day experiment with no exposure to EMF to account for any handling stress. No elevated stress levels were detected. The aims of these trials were to detect any changes in haemolymph parameters over a shorter period of time. Large crabs were utilised to allow larger volumes of haemolymph to be sampled over a short time frame.

2.2. Behavioural Analysis

2.2.1. Antennular Flicking Rate

A 12L glass tank was set up with a 40L sump tank containing UV sterilised filtered sea water that was temperature controlled (TECO TK1000) to 12°C. The experimental tank was placed on top of 4 solenoid electromagnets to create an EMF of 2.8mT. The inflow and outflow were separated from the crab inside the tank by inserting a perforated plastic sheet to reduce visual disturbance. Experimental tanks were placed behind screens to avoid external stimuli. Crabs were acclimated to the experimental tanks for 30 minutes prior to testing after which the camera was set to record via a remote control. The crab was recorded for 10 minutes under control conditions, then a further 10 minutes with an EMF present. After each trial, the tanks were sterilised and underwent a full water change to reduce chemical cues which may affect

antennular flicking rates. The system was monitored for temperature, dissolved oxygen and salinity during all trials.

The video data was post-processed with flicking rate counted for both antennules by a minimum of 3 trained people per video file for accuracy. Trials where the crab was asleep or did not exhibit any antennular flicking were discarded.

2.2.2. Activity Level and Side Selection

Four 70L experimental tanks were set up and connected to a 1000L temperature-controlled sump tank which received a constant supply of UV sterilised filtered sea water. The sides of the experimental tanks were shaded to reduce visual disturbances. A wide aperture mesh was placed over the top of the tanks to prevent the crabs from escaping. Water was pumped from the sump tank into the four experimental tanks at an equal rate for the duration of the experiment and the temperature was constantly monitored using data loggers (Onset HOBO). After each trial the tanks were drained, sterilised (Virkon aquatic) and refilled.

Four waterproof Infrared cameras were suspended above the experimental tanks and set to record during each trial. The trials consisted of:

1. Day conditions – (7 hours 30 minutes (08:30am-16:00pm)
2. Night conditions – (8 hours (20:00pm-04:00am)

The footage from each tank was post processed then analysed using Solomon Coder (version – beta 17.03.22). Each video file was broken down to still images at 1 minute intervals for the duration of the trial. The position of the crab in each image was analysed and a movement index was created by assigning a value of 0 to a picture where there was no movement, when compared to the previous picture, and a value of 1 where there was movement. The total movement index score was recorded for each tank throughout all the trials and used to indicate activity levels in the crabs. The individual pictures were analysed to determine the percentage of time each crab spent on either side of the tank (magnet or non-magnet). This was used to indicate an attraction to or avoidance of the EMF. Trials where there was no movement for the entire duration or the crab did not experience both sides of the tank were omitted. This was deemed necessary as the individual would not be making a choice based on treatment preference. It was concluded during preliminary trials that the crabs spent a significant amount of time in the corners of the tanks (approx. 85%), thus influencing magnet placement.

In the set-up the magnets were evenly spaced in the middle of one side of the tank in addition to the two magnets in the corners. Experiments were conducted under day and night conditions to fully assess the behaviour of this crepuscular species. In control conditions the magnets were present but not switched on. Magnet placement (left or right) was randomised to reduce any tank based or

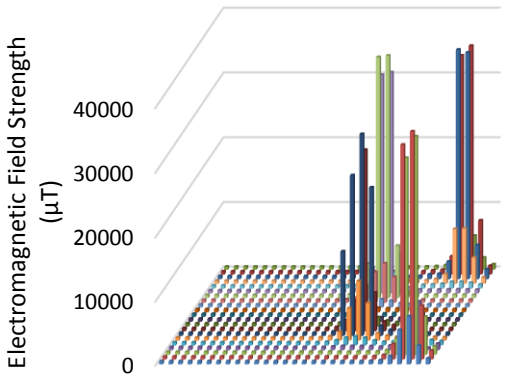

Fig. 1. Electromagnetic field strength (µT) over the tank floor (square inch) represented by the x axis. Quad magnet set-up with the corner magnets plus an additional two solenoid magnets placed just offset to create an EMF over half of the tank. Magnets were swapped randomly from the left to right sides of the tank during replication.

external stimuli that may affect results. The EMF was mapped for the setup using a 1sq. inch grid over the base of the tank with each square being measured by an AlphaLab, Inc Gaussmeter Model GM-2 (Fig. 1).

2.2.3. Shelter Selection

To further determine the effects of EMFs on crab behaviour and potential attraction, four 70L experimental tanks were set up with temperature controlled (13°C), flow through UV sterilised seawater (Fig. 2.). Six black ABS plastic shelters (300mm x 200mm x 100mm) were constructed and secured to the bottom of the tanks. In two of the tanks two plastic shelters were set up, with four solenoid electromagnets placed under each shelter. During each trial one of the shelters' electromagnets would be turned on with the other remaining off as a control. In the two remaining tanks a single shelter was set up with four solenoid electromagnets under each, one tank having the magnets switched on and the other remaining off as a control.

All magnets were set so that an EMF of 2.8mT was present under the length of the shelter. An individual large crab (121+mm carapace width) was placed in to each tank, using an even split of male and females. Using the same infrared camera set-up previously described, the crabs were recorded from 23:00pm – 06:00am and the video files post-analysed (Solomon Coder) to determine the percentage of time spent in the shelters or free roaming within the tank. The primary purpose of setting up single shelter tanks was to determine how the crab would interact with the shelter under control conditions, and to determine how the crab would act if the only shelter available is subjected to EMF. The dual shelter tanks were set up to determine if there was an attraction to EMFs and to discover how crabs would split their time between seeking shelter and active roaming.

2.3 Statistics

Results were expressed as mean ± standard error (SEM). When data met ANOVA assumptions (per Shapiro-Wilk test for normality and Levene's test for equality of error variances) multiple-comparison tests (paired t-test, one-way ANOVA, 2-way ANOVA) were conducted to reveal differences between groups. If data could not meet ANOVA assumptions, non-parametrical analysis (Wilcoxon signed rank test, Mann-Whitney, Scheirer-Ray-Hare) was performed. Chi-square test (2 tailed) was utilised for choice experiments. Post-hoc analysis for parametrical data (Tukey's test) and non-parametrical (pairwise Mann-Whitney) were conducted. All statistics were tested at a probability of 0.05 (IBM SPSS Statistics v.23 SPSS Corp. Chicago, USA).

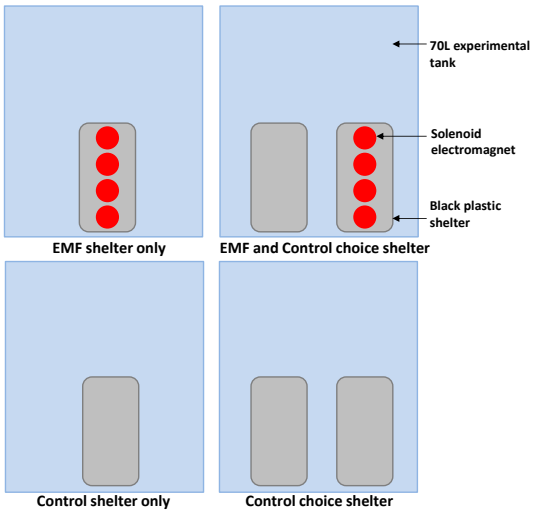

Fig. 2. The four different shelter experimental tanks. Each tank had 4 solenoid electromagnets underneath each shelter. The shelter with the electromagnets turned on was randomised along with the position of each tank to remove experimental bias and potential external variable factors. (EMF = magnets on, Control = magnets off).

3. Results

3.1. Physiological Analysis

3.1.1. Haemolymph parameters

Exposure to EMF had a significant effect on the L-Lactate levels of *Cancer pagurus* (Table 2). Throughout the 24-hour high strength (40mT) exposure L-Lactate levels followed the same circadian rhythm as the control group, with a gradual decrease in concentration throughout the day before a rise at night (Fig. 3). Despite following the same patterns, the EMF exposed values were significantly lower at 4h ($p<0.05$) and 8h ($p<0.05$) when compared to 0h. The control group showed a decrease in concentration throughout the day, however, there were no significant differences between the baseline sample and the remaining samples taken over the 24 hours. Exposure to low strength EMF (2.8mT) disrupted the natural circadian rhythm of L-Lactate causing a significant decrease throughout the 24-hour trial. The typical rise and peak values normally obtained at dawn were absent. The different EMF strengths had a significant effect on L-Lactate level ($p<0.05$). After 4 hours of exposure crabs exposed to the high strength EMF had significantly lower concentrations of L-Lactate compared to those in low strength EMF.

D-Glucose levels showed a significant increase between 0h and 4h, 0h and 8h in control crabs ($p<0.05$, $p<0.05$) and in crabs exposed to 40mT EMF ($p<0.01$, $p<0.05$) (Fig.4). Crabs exposed to 2.8mT EMF did not show the significant rise in D-Glucose level after 8h of exposure. Haemolymph D-Glucose levels of low and high strength EMF exposed crabs followed very similar daily patterns. Although D-Glucose concentrations after 4h and 8h were lower in exposed crabs compared to control, the difference was not statistically significant.

Exposure had no effect on the remaining haemolymph parameters. Hemocyanin levels remained constant (44.08±1.01mg/ml) throughout the trials, with no significant variation over time or by crab size.

To test whether EMF had any effect on the measured haemolymph stress parameters after exposure, half of the crabs used in the Helmholtz trials were sampled the following day at 0, 2, 4 and 6 hours. Exposure to EMF has no lingering effects on the haemolymph stress parameters. The increase in EMF strength from 2.8mT to 40mT had no effect on the D-Glucose or Haemocyanin parameters, but showed an overall decrease in mean L-Lactate concentration throughout the sample group. This change in concentration could potentially be explained by high individual variability or limits of the assay kit used.

3.1.2. Respiration

The mean respiration rate of juvenile crabs exposed to EMF was 0.05±0.006mg O_2/g/h, this showed no difference to values obtained from individuals under control conditions. EMF exposure did not increase O_2 demand and appears to cause no oxidative stress.

3.2 Behavioural Analysis

3.2.1. Flicking rate

Exposure to EMF caused a slight increase in antennular flicking rate in small and medium

	Helmholtz			
	L-Lactate		D-Glucose	
	EMF	Control	EMF	Control
0h	1.21±0.33	2.23±0.59	0.24±0.04	0.31±0.06
2h	1.35±0.25	1.81±0.45	0.47±0.04	0.46±0.06
4h	1.05±0.22	1.47±0.39	0.72±0.7	0.73±0.07
6h	1.03±0.23	1.22±0.47	0.81±0.08	0.71±0.08
N	20	20	20	20

Table 2 L-Lactate and D-Glucose concentrations (mM) for the Helmholtz (2.8mT) trials (Mean ± SEM).

Figure 3.

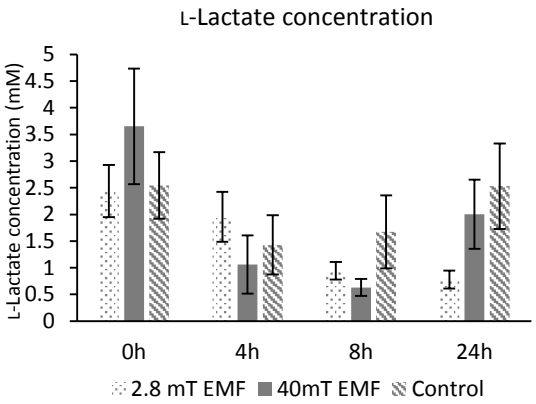

Figure 4.

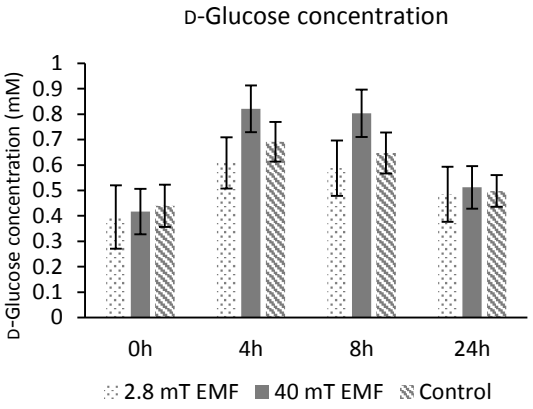

Figure 3., Figure 4. L-Lactate (Fig. 3.) and D-Glucose concentrations (Fig. 4.) (Mean ± SEM) over a 24-hour period during control conditions and exposure to low strength (2.8mT) and high strength (40mT) EMF. In the control over 24-hours both parameters show a natural circadian rhythm with an increase leading up to and during the night. The L-Lactate circadian rhythm was disrupted by exposure to 2.8mT EMF and did not follow the usual trend, showing a continuous decrease and significantly lower values after 24 hours. The L-Lactate circadian rhythm was altered during exposure to 40mT EMF resulting in much lower concentrations after 4h and 8h despite following the same trend found in the control results. D- Glucose levels followed similar circadian rhythm in control and 40 mT EMF exposed crabs, with significant increase towards peak locomotor activity, while 2.8 mT exposed crabs were lacking this increase and showed no significant elevation after 8 h.

crabs although this was not statistically significant (Fig. 5). The average pre-EMF flicking rate of 22±4 flicks/min remained unchanged during exposure to EMF (24±4 flicks/min). The mean flicking rate in the first minute of exposure to EMF (25±4 flicks/min) remained unchanged from initial measurements in control conditions (25±4 flicks/min).

3.2.2. Activity level

During day conditions, there was no significant difference in activity levels between EMF exposed crabs and control, with size being the only significant factor (Fig. 6). The decrease in activity level corresponds with an increase in crab size, with small crabs (19.6±2.5%) having higher activity levels than large crabs (10.1±3.2%). During night conditions, there was a significant increase in activity levels for all size groups. Small (42.7±5.6%) and medium crabs (45.5±5.1%) had significantly higher activity levels than large crabs (25.9±2%).

3.2.3. Side selection

Under control conditions crabs spent significantly more time on one side of the tank in both day (32-68%) and night (36-64%) conditions (N=96). When there was an EMF present there were no clear preferences made

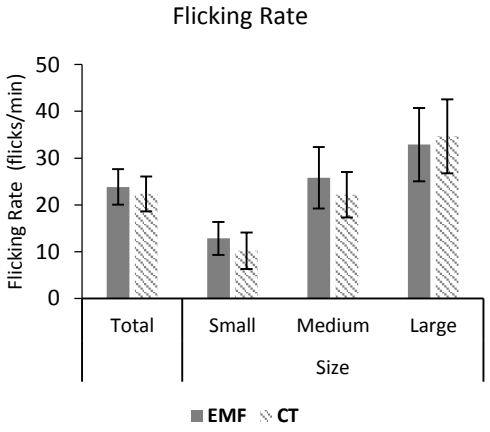

Fig. 5. Antennular flicking rate (Mean ± SEM) of individuals exposed to EMF and control conditions for the three size groups (N=30) and combined.

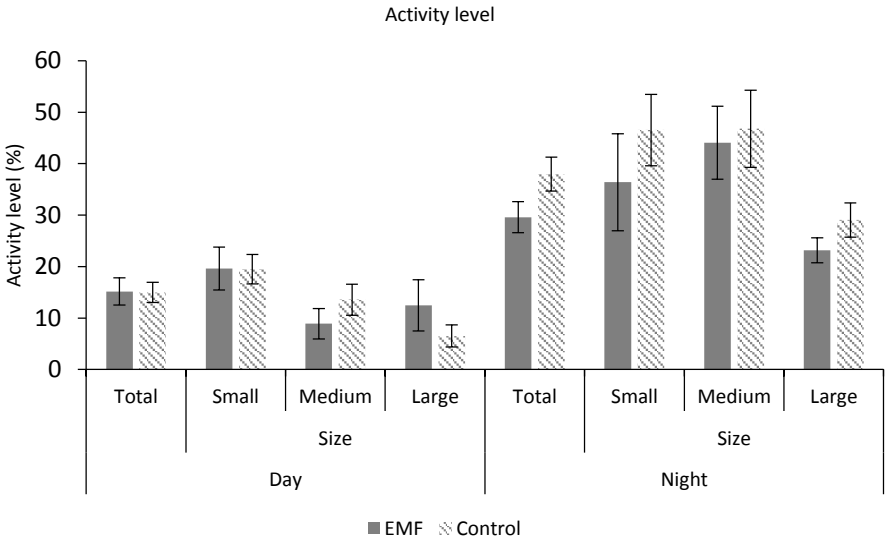

Fig. 6. Activity level (Mean ± SEM) of the different size groups in both treatments for day and night conditions. (N_{DAY}=79, N_{NIGHT}=117).

between sides during both day (44-56%) and night (50-50%) conditions (N=99). There was a significant difference between control and EMF exposed crabs' mean side selection for both day ($p<0.05$, N=77) and night ($p<0.05$, N=118). This shows that in the presence of an EMF individual crabs fail to make a clear side preference.

3.2.4. Shelter selection

3.2.4.1. Single shelter

The mean time spent in the shelter (48%) and out (52%) was approximately equal in the control trials (Fig. 7B). When there was an EMF present in the shelter the proportion of mean time spent within the shelter increased to 69% (Fig. 7A). These trials also confirmed what was discovered in the dual shelter set ups in that the percentage time spent roaming the tank significantly decreases from 52% in the control to 31% when there was an EMF present. The overall mean percentage time spent in both locations was significantly different between control and EMF conditions ($p<0.001$).

3.2.4.2. Dual shelter

Under control conditions the mean time spent in each shelter and out roaming in the tank were equal (35% EMF shelter, 31% CT shelter and 34% No shelter) (Fig. 7D). During EMF exposure, there were clear preferences for the shelter with the EMF present resulting in 69% mean time spent within, with only 9% spent in the control shelter and 22% spent roaming the tank (Fig. 7C). There was a drop in mean time from 34% under control conditions to 22% during EMF exposure suggests that once the crabs detect EMFs they will begin to seek shelter and are drawn to the shelter with the EMF emanating from within. The overall mean percentage time spent in all three locations was significantly different between control and EMF conditions ($p<0.001$). Throughout all shelter trials an equal number of male and female crabs were used. There were no significant differences in behaviour between the sexes.

4. Discussion

4.1. Physiological Analysis

4.1.1. Haemolymph parameters

L-Lactate and D-Glucose both followed a natural circadian rhythm with a rise in D-Glucose, and a subsequent fall in L-Lactate concentrations throughout the day. L-Lactate

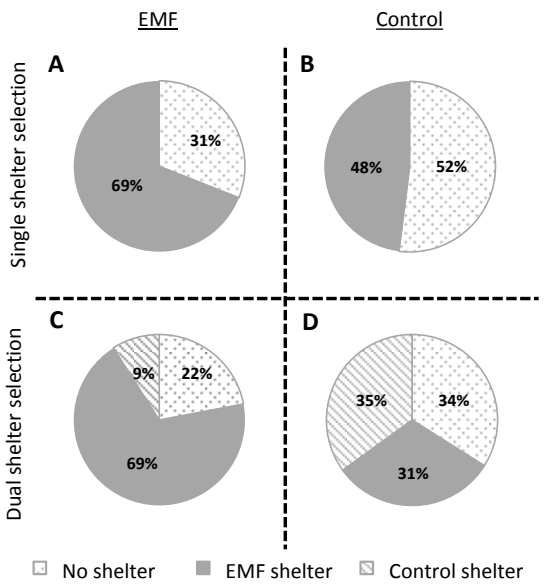

Fig. 7. Effect of EMF on shelter selection. Time spent in single shelter and outside of the shelter, if exposed to EMF (A) and when the magnets are switched off (B). EMF (N=11) and control (N=11). Time spent in each shelter and outside the shelters, when one of the shelter is exposed to EMF (C) and if none are exposed (D). EMF (N=15) and control (N=15) Shown as a percentage of total trial time (%).

levels rise throughout the night due to increased activity and subsequent increase in glucose metabolism. In crustaceans, haemolymph glucose and lactate levels are affected by various environmental conditions and stressors (Kallen *et al*. 1990, Reddy *et al*. 1996, Chang *et al*. 1998,) and should cycle together under normal, unstressed conditions. L-Lactate is an indicator of anaerobic respiration, typically due to impaired gill function or hypoxic conditions (Durand *et al.* 2000). D-Glucose, the primary fuel for ATP production in crustaceans is crucial in maintaining metabolic processes (Barrento *et al*. 2010). D-Glucose levels show a negative correlation with vigour where healthy individuals have lower levels and moribund crabs become hyperglycaemic (Barrento *et al.* 2010). Activity levels in crabs should partially be reflected in D-Glucose concentrations (Briffa and Elwood 2001). D-Glucose levels were found to correlate well with current literature in that there was a continual rise in concentration in relation to locomotor activity (Hamann 1974; Reddy *et al*. 1981; Kallen *et al.* 1988; Kallen *et al.* 1990; Tilden *et al.* 2001). This suggests that D-Glucose levels continually rise throughout the night until peak locomotor activity has been reached during which the levels will begin to decrease back to original values. EMF exposure did not significantly influence activity level which is consistent with minor changes in D-Glucose levels. Several studies have shown that EMF can alter the circadian rhythm of animals through altering melatonin levels (Reiter 1993; Schneider *et al.* 1994; Levine *et al* 1995; Wood *et al.* 1998). Melatonin, a neuropeptide, present in crustaceans, can cause shifts in L-Lactate and D-Glucose cycles (Tilden *et al.* 2001). This suggests that exposure to a field of 2.8mT could affect melatonin secretion, which consequently alters L-Lactate and D-Glucose circadian rhythms. At 2.8mT, the L-Lactate concentration follows the circadian rhythm and decreases throughout the day when activity levels are generally lower. During the night there were no differences in activity levels between 2.8mT and control crabs, however there were no increases in L-Lactate levels.

The suppression of the rise in L-Lactate prevents the increase in O_2 affinity of Haemocyanin that would naturally occur (Sanders and Childress 1992). An increase in L-Lactate has been shown to occur in *Carcinus maenas* during emersion when the crabs would be relying on anaerobic respiration.

During re-immersion L-Lactate levels remained elevated after 1 hour suggesting that the crabs have to repay an oxygen debt (Simonik and Henry 2014). Exposure to EMF supresses the rise in L-Lactate which enables the crabs to repay the oxygen debt accrued during periods of higher activity. During long exposures to EMF, crabs may be unable to repay this oxygen debt, potentially leading to increased mortality. Both D-Glucose and L-Lactate concentrations show high individual variability with D-Glucose levels influenced by individual status and reactions to external stimulus (Matsumasa and Murai 2005). The values observed for L-Lactate and D-Glucose corresponded with those found in previous literature (Watt *et al.* 1999; Lorenzon *et al.* 2008; Barrento *et al.* 2010; Barrento *et al.* 2011). Haemocyanin, as the primary oxygen carrying protein in invertebrates, has been shown to increase in concentration during periods of hypoxia (Hagerman et al. 1990). The lack of deviation in concentrations observed suggests that EMF exposure does not elicit similar physiological responses as hypoxic conditions. The overall lack of change on these parameters suggests this species can maintain homeostasis during exposure to high strength EMFs.

4.1.2. Respiration

Although increased oxygen demand and high gill ventilation rates typically occur in crustaceans subjected to different stressors (Jouve-Duhamel and Truchot 1985; Paterson and Spanoghe 1997), EMF (2.8mT) did not significantly alter the respiration rate of juvenile crabs. Respiration rates in *Cancer pagurus* are highly variable due to the alternating periods of apnoea and bradycardia that have been observed in pausing behaviour (Bottoms, 1977; Burnett and Bridges, 1981). This pausing behaviour will alternate but can be present for significant periods of time. This was concluded by Burnett and Bridges (1981) when individuals were found to be exhibiting pausing behaviour for 40-50% of the time. These results show that juvenile *Cancer pagurus* respiration levels correlate well with other species of crabs of similar size: velvet swimming crab, *Necora puber*, (0.21 ±0.119 mg O_2/g/h (Small *et al.* 2010)); spider crab, *Hyas araneus*, (0.025 mg O_2/g/h (Camus *et al.* 2002)); Dungeness crab, *Cancer magister*, (0.044 mg O_2/g/h (Johansen *et al.* 1970)) and shore crab, *Carcinus maenas*, (0.036 - 0.126 mg O_2/g/h (Newell *et al.* 1972; Taylor and Wheatly 1979). Current respiration values for adult *Cancer pagurus* found in the literature are 28.03mg O_2/g/h during pre-pause and 4.42 mg O_2/g/h post pause (Bradford and Taylor 1982).

4.2. Behavioural Analysis

4.2.1. Flicking rate

The lack of deviation in the number of antennular flicks during initial exposure and throughout the trials suggest that the antennules may not be utilized in the detection of EMF in this species, or as a reliable indicator of detection. Similar results were reported by Woodruff *et al.* (2013) after exposing Dungeness crab, *Metacarcinus magister*, to a 3mT EMF.

4.2.2. Activity level

Exposure to EMF did not have any effect on the overall activity level in *Cancer pagurus*. This suggests that if there is a behavioural change during exposure to EMF it may be more subtle than basic movement levels. The side selection results confirm that there is a decreased ability to find a suitable resting spot, however the crabs did not have higher activity levels within the EMF treatment. Under control conditions the crabs alternated their time between resting and roaming, subsequently spending larger amounts of time resting in the same spot. EMF exposure did not affect the resting and roaming behaviour but appeared to inhibit

the crabs from spending large amounts of time in the same location. Overall activity levels were not affected by EMF exposure, but the distribution of time spent in specific locations (see 4.2.3.) within the tank and between resting and roaming behaviours were. The low activity levels during the day could be a result of behaviour consisting largely of shelter seeking (Chapman and Rice 1971; Hockett and Kritzler 1972; Hazlett and Rittschof 1975; Hill 1976). The discrepancies between size groups could be explained by smaller crabs typically inhabiting the sub-littoral zone where there will be higher risks of predation and higher competition for food and shelter, whereas larger crabs which tend to be found in deeper waters may not be subjected to the same pressures as the juveniles given their larger size (Paine 1976). The increase in activity levels during the night corresponds with this species' nocturnal behaviour and will be due to foraging or potential mate seeking (Seed 1969; Skajaa *et al.* 1998). The increase in antennular flicking rate of larger crabs combined with the decreased activity levels suggest that adult crabs rely more on chemical sensing than physical exploration to survey the environment.

4.2.3. Side selection

Exposure to EMF does not affect the activity levels of the crabs but affects their ability to select a site to rest. This may be explained by crabs seeking shelter (see 4.2.4 below) when they detect EMF as opposed to natural movement patterns (Skajaa *et al.* 1998) observed in those within the control group. The crabs under control conditions spent a higher percentage of their time on one side of the tank interspersed with active roaming. EMF exposure inhibited a clear side preference within the tank which resulted in an approximately 50-50% split across the tank, potentially reflecting shelter seeking behaviour. *Cancer pagurus* has been shown to inhabit pits when inactive (Hall *et al.* 1991) and were observed spending large amounts of time resting during the day in acclimation tanks with minimal movement. This behaviour appears to have been altered by exposure to EMF.

4.2.4. Shelter selection

During the single shelter trials when crabs were exposed to control conditions there was an equal amount of time spent inside and outside the shelters. The same pattern was recorded during the dual shelter trials, with an equal amount of time spent in each of the shelters and roaming the tank. This suggests that when there are no environmental stressors present the crabs will spend a portion of their time resting in shelter and an equal portion of their time surveying their environment exhibiting roaming behaviour. When there was an EMF present the amount of time spent exhibiting roaming behaviour significantly decreased in both single and dual shelter trials. This has clear implications on the *Cancer pagurus* population in the areas surrounding MREDs. If there is an EMF present then crabs will be drawn to the source of the emission and spend significant amounts of time within the affected area. This will come at the cost of time spent foraging for food, seeking mates and finding shelter, potentially leading to higher predation rates, increased death due to starvation and/or decreased number of successful matings. Many offshore sites have introduced no-take zones around turbine arrays, with speculation that the decrease in fishing pressure, combined with the addition of artificial reefs in the form of scour protection blocks, could enhance the overall crustacean population (Langhamer and Wilhelmsson 2009) by providing refuge and breeding areas. However, this experiment highlights the potential lack of spill-over effect from these areas due to a high attraction to the emitted EMF. This suggests that fishing zones in close proximity to subsea power cables

could potentially see an overall decrease in crab numbers. Scour protection zones are estimated to create 2.5 times more habitat than is lost by array installation (Linley *et al.* 2009) and with the inclusion of drilled holes have an estimated carrying capacity of 65,000kg of fish per year per turbine (Linley *et al.* 2009). If specific habitat requirements are considered for individual target species around MREDs during the construction of these artificial habitats, then abundance and diversity of associated species, including commercially important species, could be enhanced (Bortone *et al.* 1994; Kawasaki *et al.* 2003) subject to EMF emission mitigation.

5. Conclusion

Several decapod crustaceans are known to be magneto sensitive, yet information available on the effects of electromagnetic fields emitted from MREDs is scarce. The aim of this study was to fill some of these knowledge gaps. Exposure to electromagnetic fields, of the strength predicted around sub-sea cables, had significant physiological effects on *Cancer pagurus* and changed their behaviour. EMF disrupted the circadian rhythm of haemolymph L-Lactate and D-Glucose levels. Melatonin levels in several species have been found to be affected by EMF exposure. This suggests that EMF exposure could affect crustaceans on a hormonal level. Further studies are needed to understand the underlying mechanism responsible for disrupted glucose and lactate cycles.

In this study it was shown that EMF exposure altered behaviour, with crabs spending less time roaming around the tank and more time in a shelter in direct contact with the EMF. This suggests that the natural roaming behaviour, where individuals will actively seek food and/or mates has been overridden by an attraction to the source of the EMF. When given the choice between a shelter exposed to EMF and one without exposure, the crabs were always drawn to the EMF. These results predict that in benthic areas surrounding MREDs, where there is increased EMFs, there will be an increase in the abundance of *Cancer pagurus* present. This potential aggregation of crabs around benthic cables and the subsequent physiological changes in L-Lactate and D-Glucose levels, brought about by EMF exposure, is a cause for concern.

Berried female Edible crabs move offshore and spend 6-9 months, buried with minimal movement and lower feeding rates (Williamson, 1900; Edwards, 1979; Howard, 1982; Naylor *et al.,* 1997). Given this species' proven attraction to EMF sources, incubation of the eggs may take place around areas with increased EMF emissions. Long term studies are needed to investigate the effects of chronic EMF exposure. The effects of EMF on egg development, hatching success and larval fitness are unknown and need to be addressed. As larval stages are critical population bottlenecks, any negative effect of EMF on crab larvae will have a drastic effect on the edible crab fishery.

With the recent large scale renewable energy developments, it is clear more research is needed to reduce uncertainty of the environmental effects of these activities on benthic marine species, particularly on other commercially and ecologically important decapod crustaceans. This is important to develop an understanding of population level consequences and cumulative impacts of MREDs' stressors. These knowledge gaps need to be addressed before the implementation of the many approved wind farm sites around the UK to help mitigate an ever growing problem.

References

1. Bannister, C. 2009. On the management of brown crab fisheries. *London: Shellfish Association of Great Britain*.
2. Barrento, S., Marques, A., Vaz-Pires, P., & Nunes, M. L. 2010. Live shipment of immersed crabs Cancer pagurus from England to Portugal and recovery in stocking tanks: stress parameter characterization. ICES Journal of Marine Science: Journal du Conseil, 67(3), 435-443.
3. Barrento, S., Marques, A., Vaz-Pires, P., & Nunes, M. L. 2011. Cancer pagurus (Linnaeus, 1758) physiological responses to simulated live transport: Influence of temperature, air exposure and AQUI-S®. *Journal of Thermal Biology*, *36*(2), 128-137.
4. Bergmann, M., Taylor, A. C., & Moore, P. G. 2001. Physiological stress in decapod crustaceans (Munida rugosa and Liocarcinus depurator) discarded in the Clyde Nephrops fishery. Journal of Experimental Marine Biology and Ecology, 259(2), 215-229.
5. Bilgili, M., Yasar, A. and Simsek, E., 2011. Offshore wind power development in Europe and its comparison with onshore counterpart. Renewable and Sustainable Energy Reviews, 15(2), pp.905-915.
6. Bochert, R., & Zettler, M. L. 2006. Effect of electromagnetic fields on marine organisms. In Offshore Wind Energy (pp. 223-234). Springer Berlin Heidelberg.
7. Bortone, S.A., Martin, T. and Bundrick, C.M., 1994. Factors affecting fish assemblage development on a modular artificial reef in a northern Gulf of Mexico estuary. Bulletin of Marine Science, 55(2-3), pp.319-332.
8. Bottoms, A. 1977. Some aspects of the respiratory physiology of Cancer pagurus (L.) (Crustacea: Decapoda) in Scottish West Coast waters. Ph.D. Thesis, University of Stirling.
9. Bradford, S.M. and Taylor, A.C., 1982. The respiration of Cancer pagurus under normoxic and hypoxic conditions. Journal of Experimental Biology,97(1), pp.273-288.
10. Briffa, M., & Elwood, R. W. 2001. Decision rules, energy metabolism and vigour of hermit–crab fights. Proceedings of the Royal Society of London B: Biological Sciences, 268(1478), 1841-1848.
11. Brown, C. J., Saunders, M. I., Possingham, H. P., & Richardson, A. J. 2013. Managing for interactions between local and global stressors of ecosystems. PloS one, 8(6), e65765.
12. Burnett, L. E. & Bridges, C. R. 1981. The physiological properties and functions of ventilatory pauses in the crab Cancer pagurus .J. comp. Physiol. (in the Press.)
13. Camus, L., Jones, M. B., Børseth, J. F., Regoli, F., & Depledge, M. H. 2002. Heart rate, respiration and total oxyradical scavenging capacity of the Arctic spider crab, Hyas araneus, following exposure to polycyclic aromatic compounds via sediment and injection. Aquatic toxicology, *61*(1), 1-13.
14. Chang ES., Keller R., Chang SA. 1998. Quantification of crustacean hyperglycemic hormone by ELISA in hemolymph of the lobster, Homarus americanus, following various stresses. Gen Comp Endocrinol 111:359–366.
15. Chapman, C.J. and Rice, A.L., 1971. Some direct observations on the ecology and behaviour of the Norway lobster Nephrops norvegicus. Marine Biology, 10(4), pp.321-329.
16. Chowdhury, S., Zhang, J., Messac, A. and Castillo, L., 2012. Unrestricted

wind farm layout optimization (UWFLO): Investigating key factors influencing the maximum power generation. Renewable Energy, 38(1), pp.16-30.

17. CMACS 2003 A baseline assessment of electromagnetic fields generated by offshore windfarm cables. COWRIE Report EMF - 01-2002 66.
18. Doney, S. C., Ruckelshaus, M., Duffy, J. E., Barry, J. P., Chan, F., English, C. A., . & Polovina, J. 2012. Climate change impacts on marine ecosystems. Marine Science, 4.
19. Durand, F., Devillers, N., Lallier, F. H., & Regnault, M. 2000. Nitrogen excretion and changes in blood components during emersion of the subtidal spider crab Maia squinado (L.). Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 127(3), 259-271.
20. Edwards, E. 1979. The edible crab and its fishery in British waters.
21. Frid, C., Andonegi, E., Depestele, J., Judd, A., Rihan, D., Rogers, S.I. and Kenchington, E., 2012. The environmental interactions of tidal and wave energy generation devices. Environmental Impact Assessment Review, 32(1), pp.133-139.
22. Garthe, S., & Hüppop, O. 2004. Scaling possible adverse effects of marine wind farms on seabirds: developing and applying a vulnerability index. Journal of applied Ecology, 41(4), 724-734.
23. Gill, A. B. 2005. Offshore renewable energy: ecological implications of generating electricity in the coastal zone. Journal of Applied Ecology, 42(4), 605-615.
24. Hagerman, L., Søndergaard, T., Weile, K., Hosie, D., & Uglow, R. F. 1990. Aspects of blood physiology and ammonia excretion in Nephrops norvegicus under hypoxia. Comparative Biochemistry and Physiology Part A: Physiology, 97(1), 51-55.
25. Haig, J.A.; Pantin, J.R.; Salomonsen, H. & M.J. Kaiser 2015. Size at maturity of the edible crab (Cancer pagurus) in Welsh waters. Fisheries & Conservation Science report No 51, Bangor University. Pp.26.
26. Hall, S.J., Basford, D.J., Robertson, M.R., Raffaelli, D.G. and Tuck, I., 1991. Patterns of recolonisation and the importance of pit-digging by the crab Cancer pagurus in a subtidal sand habitat. Marine Ecology Progress Series, pp.93-102.
27. Hamann, A. 1974. Die neuroendokrine Steuerung tagesrhythmischer Blutzuckerschwankungen durch die Sinusdrüse beim Flusskrebs. *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology*, *89*(2), 197-214.
28. Harris, R. and Andrews, M., 2005. Physiological changes in the Norway lobster Nephrops norvegicus (L.) escaping and discarded from commercial trawls on the West Coast of Scotland. 1. Body fluid volumes and haemolymph composition after capture and during recovery. *Journal of experimental marine biology and ecology*, *320*(2), pp.179-193.
29. Hazlett, B. and Rittschof, D., 1975. Daily movements and home range in Mithrax spinosissimus (Majidae, Decapoda). Marine & Freshwater Behaviour & Phy, 3(2), pp.101-118.
30. Hockett, J.C. and Kritzler, H., 1972. Capture-recapture methods with Uca. The Biological Bulletin, 142(1), pp.49-56.
31. Howard, A. E. 1982. The distribution and behaviour of ovigerous edible crabs (Cancer pagurus), and consequent sampling bias. Journal du Conseil, 40(3), 259-261.

32. Johansen, K., Lenfant, C., & Mecklenburg, T. A. 1970. Respiration in the crab, Cancer magister. *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology*, *70*(1), 1-19.
33. Jouve-Duhamel, A., & Truchot, J. P. 1985. Ventilatory responses to ambient oxygen in stressed and fully settled shore crabs Carcinus maenas (L.). *Journal of experimental marine biology and ecology*, *90*(2), 107-118.
34. Kallen, J. L., Rigiani, N. R., & Trompenaars, H. J. A. J. 1988. Aspects of Entrainment of CHH Cell Activity and Hemolymph Glucose Levels in Crayfish. The Biological Bulletin, 175(1), 137-143.
35. Kallen, J. L., Abrahamse, S. L., & Van Herp, F. 1990. Circadian rhythmicity of the crustacean hyperglycemic hormone (CHH) in the hemolymph of the crayfish. The Biological Bulletin, 179(3), 351-357.
36. Kawasaki, H., Sano, M. and Shibuno, T., 2003. The relationship between habitat physical complexity and recruitment of the coral reef damselfish, Pomacentrus amboinensis: an experimental study using small-scale artificial reefs. Ichthyological Research, 50(1), pp.0073-0077.
37. Landers Jr, D. F., Keser, M., & Saila, S. B. 2001. Changes in female lobster (Homarus americanus) size at maturity and implications for the lobster resource in Long Island Sound, Connecticut. Marine and Freshwater Research, 52(8), 1283-1290.
38. Langhamer, O. and Wilhelmsson, D., 2009. Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes–a field experiment. Marine Environmental Research, 68(4), pp.151-157.
39. Levine, R. L., Dooley, J. K., & Bluni, T. D. 1995. Magnetic field effects on spatial discrimination and melatonin levels in mice. Physiology & behavior, 58(3), 535-537.
40. Lindeboom, H. J., Kouwenhoven, H. J., Bergman, M. J. N., Bouma, S., Brasseur, S. M. J. M., Daan, R, & Lambers, R. H. R. 2011. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. Environmental Research Letters, 6(3), 035101.
41. Linley, A., Laffont, K., Wilson, B., Elliot, M., Perez-Dominguez, R. and Burdon, D., 2009. Offshore and Coastal Renewable Energy: Potential ecological benefits and impacts of large-scale offshore and coastal renewable energy projects. PML Applications Ltd, SAMS, IECS. Marine Renewables Scoping Study NERC Final report. 124p.
42. Lorenzon, S., Giulianini, P. G., Martinis, M., & Ferrero, E. A. 2007. Stress effect of different temperatures and air exposure during transport on physiological profiles in the American lobster Homarus americanus. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *147*(1), 94-102.
43. Matsumasa, M., & Murai, M. 2005. Changes in blood glucose and lactate levels of male fiddler crabs: effects of aggression and claw waving. Animal Behaviour, 69(3), 569-577.
44. Naylor, J. K., Taylor, E. W., & Bennett, D. B. 1997. The oxygen uptake of ovigerous edible crabs (Cancer pagurus)(L.) and their eggs. Marine & Freshwater Behaviour & Phy, 30(1), 29-44.
45. Newell, R. C., Ahsanullah, M., & Pye, V. I. 1972. Aerial and aquatic respiration in the shore crab Carcinus maenas(L.). *Comparative Biochemistry and Physiology Part A: Physiology*, *43*(2), 239-252.

46. Nichols, J. H., Thompson, B. M., & Cryer, M. 1982. Production, drift and mortality of the planktonic larvae of the edible crab (Cancer pagurus) off the north-east coast of England. Netherlands Journal of Sea Research, 16, 173-184.
47. Normandeau, Exponent, T. Tricas, and A. Gill. 2011. Effects of EMFs from Undersea Power Ocean Energy Management, Regulation, and Enforcement, Pacific OCS Region, Camarillo, CA.OCS Study BOEMRE 2011-09.
48. Offshore wind electricity - The Crown Estate. (n.d.). Retrieved June 14, 2017, from https://www.thecrownestate.co.uk/energy-minerals-and-infrastructure/offshore-wind-energy/
49. Öhman, M. C., Sigray, P., & Westerberg, H. 2007. Offshore windmills and the effects of electromagnetic fields on fish. AMBIO: A journal of the Human Environment, 36(8), 630-633.
50. Paine, R.T., 1976. Size-limited predation: an observational and experimental approach with the Mytilus-Pisaster interaction. Ecology, 57(5), pp.858-873.
51. Paterson, B. D., & Spanoghe, P. T. 1997. Stress indicators in marine decapod crustaceans, with particular reference to the grading of western rock lobsters (Panulirus cygnus) during commercial handling. Marine and freshwater research, 48(8), 829-834.
52. Pimentel, D., Herz, M., Glickstein, M., Zimmerman, M., Allen, R., Becker, K., & Seidel, T. 2002. Renewable Energy: Current and Potential Issues Renewable energy technologies could, if developed and implemented, provide nearly 50% of US energy needs; this would require about 17% of US land resources. Bioscience, 52(12), 1111-1120.
53. Reddy, D. C., Raghupathi, M., Purushotham, K. R., & Naidu, B. P. 1981. Daily rhythms in levels of blood glucose & hepatopancreatic glycogen in the fresh water field crab Oziotelphusa senex (Fabricius).
54. Reddy PS, Katyayani RV, Fingerman M. 1996. Cadmium and naphthalene-induced hyperglycemia in the fiddler crab, Uca pugilator: Differential modes of action on the neuroendocrine system. Bull Environ Contam Toxicol 56: 425–431.
55. Reiter, R. J. 1993. Static and extremely low frequency electromagnetic field exposure: reported effects on the circadian production of melatonin. Journal of cellular biochemistry, 51(4), 394-403.
56. Sanders, N.K. and Childress, J.J., 1992. Specific effects of thiosulphate and L-lactate on hemocyanin-O2 affinity in a brachyuran hydrothermal vent crab. Marine Biology, 113(2), pp.175-180.
57. Schneider, T., Thalau, H. P., & Semm, P. 1994. Effects of light or different earth-strength magnetic fields on the nocturnal melatonin concentration in a migratory bird. Neuroscience letters, 168(1), 73-75.
58. Seed, R., 1969. The ecology of Mytilus edulis L.(Lamellibranchiata) on exposed rocky shores. Oecologia, 3(3-4), pp.317-350.
59. Simonik, E. and Henry, R.P., 2014. Physiological responses to emersion in the intertidal green crab, Carcinus maenas (L.). Marine and freshwater behaviour and physiology, 47(2), pp.101-115.
60. Skajaa, K., Fernö, A., Løkkeborg, S., & Haugland, E. K. 1998. Basic movement pattern and chemo-oriented search

towards baited pots in edible crab (Cancer pagurus L.). In Advances in Invertebrates and Fish Telemetry (pp. 143-153). Springer Netherlands.

61. Small, D., Calosi, P., White, D., Spicer, J. I., & Widdicombe, S. 2010. Impact of medium-term exposure to CO2 enriched seawater on the physiological functions of the velvet swimming crab Necora puber. *Aquatic Biology*, *10*(1), 11-21.
62. Smith, I. P., Collins, K. J., & Jensen, A. C. 1999. Seasonal changes in the level and diel pattern of activity in the European lobster Homarus gammarus. Marine Ecology Progress Series, 186, 255-264.
63. Stoner, A.W. 2012. Assessing stress and predicting mortality in economically significant crustaceans. *Reviews in Fisheries Science* 20, 111-135.
64. Taylor, E. W., & Wheatly, M. G. 1979. The behaviour and respiratory physiology of the shore crab, Carcinus maenas (L.) at moderately high temperatures. *Journal of Comparative Physiology B: Biochemical, Systemic, and Environmental Physiology*, *130*(4), 309-316.
65. Taylor, H. H., Paterson, B. D., Wong, R. J., & Wells, R. M. G. 1997. Physiology and live transport of lobsters: report from a workshop. Marine and Freshwater Research, 48(8), 817-822.
66. Thomsen, F., Gill, A., Kosecka, M., Andersson, M., Andre, M., Degraer, S., & Norro, A. 2015. MaRVEN-Environmental impacts of noise, vibrations and electromagnetic emissions from marine renewable energy-Final study report. DG RTD (Directorate-General for Research and Innovation of the European Commission).
67. Tilden, A., McGann, L., Schwartz, J., Bowe, A., & Salazar, C. 2001. Effect of melatonin on hemolymph glucose and lactate levels in the fiddler crab Uca pugilator. Journal of Experimental Zoology Part A: Ecological Genetics and Physiology, 290(4), 379-383.
68. Walker, M. M., Diebel, C. E., & Kirschvink, J. L. 2003. Detection and use of the earth's magnetic field by aquatic vertebrates. In Sensory processing in aquatic environments (pp. 53-74). Springer New York.
69. Watt, A. J. S., Whiteley, N. M., & Taylor, E. W. 1999. An in situ study of respiratory variables in three British sublittoral crabs with different routine rates of activity. *Journal of experimental marine biology and ecology*, *239*(1), 1-21.
70. Westerberg, H., & Lagenfelt, I. 2008. Sub-sea power cables and the migration behaviour of the European eel. Fisheries Management and Ecology, 15(5-6), 369-375.
71. Williamson, H. C. 1900. Contributions to the life-history of the edible crab (Cancer pagurus, Linn.). Fishery Board of Scotland.
72. Wood, A. W., Sait, M. L., Armstrong, S. M., & Martin, M. J. 1998. Effects of 50 Hz magnetic fields on human physiology: plasma melatonin levels. In Bioelectromagnetism, 1998. Proceedings of the 2nd International Conference on (pp. 161-162). IEEE.
73. Woodruff, D. L., Schultz, I. R., Marshall, K. E., Ward, J. A., & Cullinan, V. I. 2013. *Effects of Electromagnetic Fields on Fish and Invertebrates: Task 2.1. 3: Effects on Aquatic Organisms-Fiscal Year 2011 Progress Report-Environmental Effects of Marine and Hydrokinetic Energy* (No. PNNL-20813 Final). Pacific Northwest National Laboratory (PNNL), Richland, WA (US).