Applying Ecological Risk Assessment Methodology for Outlining Ecosystem Effects of Ocean Energy Technologies

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Abstract— **With the increasing utilization of marine space and resources, ecosystem-based approaches to environmental assessments are requested. In this study the Ecological Risk Assessment (EcoRA) framework was used to outline risks from three ocean energy technologies; wave power, tidal current power, and ocean thermal energy conversion (OTEC). Our findings show that the potential risks from these new technologies include a multitude of ecosystem components and biological processes, which stretch over large spatiotemporal scales and motivate, the use of ecosystem-level assessment endpoints. In order to structure environmental assessments with such complex scope, assessment endpoints may preferably be associated with resilience in terms of maintaining ecosystem services. Moreover, cumulative effects from multiple stressors should be included. The systematic EcoRA methodology seems an appropriate tool for proactively assessing the risks from new technologies, such as ocean energy, in the complex and strained ocean environment.**

***Keywords*— Ecological Risk Assessment, Ecosystem-based management, Environmental impacts, ocean thermal energy conversion, resilience, scale, tidal current power, wave power**

I. Introduction

Ocean energy comprises a set of new technologies aiming at large scale extraction of renewable energy from the sea [1] [2]. Despite being environmentally benign from a climate change perspective, ocean energy technologies may act as local stressors to the ecosystem where they are employed [3]. The pressure on marine ecosystems from human activities is already massive [4] [5], a gloomy prerequisite that has to be taken into account when considering further utilization of the sea. Current approaches to environmental impact assessment in the ocean sphere emphasize a need for ecosystem-based management and marine spatial planning (MSP) [6]. It is, however, not obvious how this ambition is best executed in practice [7].

An ecosystem-based approach means that emphasis must be allocated not only on the most obvious affected elements but also on the secondary and broader components of the ecosystem, which in ecological terms means not only on the affected populations but also on ecosystem processes and interactions between the different processes in space and time. MSP, in turn, implies that focus is lifted from single stressor sources to grasp the full range of concurrently operating and potential human activities, thus applying proactive and inclusive planning for each section of the marine environment [8].

From these standpoints upcoming marine technologies, such as ocean energy, have to be considered from a broader perspective than by the awaited heap of project-based environmental impact assessments, if to be sustainably integrated among the various ecological components and concurrent human activities. At a higher level, strategic environmental assessments and regulatory authority MSP, e.g. [8], may turn out to function well in safeguarding such a broader focus. A corresponding wide-ranging outlook should also be incorporated at the more rapid project level, in particular since both MSP procedures and ocean energy technologies are relatively new to the world. Among the many tools in the field of environmental assessment ecological risk assessment (EcoRA), which focuses on selected valued endpoints rather than on the technology itself, may be particularly suitable for keeping focus on a complex environment with a multitude of stressors.

In this study, we have used the EcoRA framework to outline ecosystem-based endpoints and stressor pathways from three different ocean energy technologies. The selected technologies were wave power, tidal current power, and ocean thermal energy conversion (OTEC). The current state of knowledge regarding environmental impacts of the three selected ocean energy technologies was inventoried and used as a basis for discussing the applicability of EcoRA as well as how to approach the inevitable interactions with impacts from other co-occurring stressors (cumulative effects).

II. Fundamentals of Ecological Risk Assessments

Risk is basically a measure of the probability and the magnitude of adverse consequences of an event [9]. The aim of any risk assessment is to provide decision-makers with a quantified estimate, or at least a ranking, of the potential hazardous effects of optional decisions for which the outcomes are not completely understood. Considerations regarding the location and design of ocean energy projects would be an example.

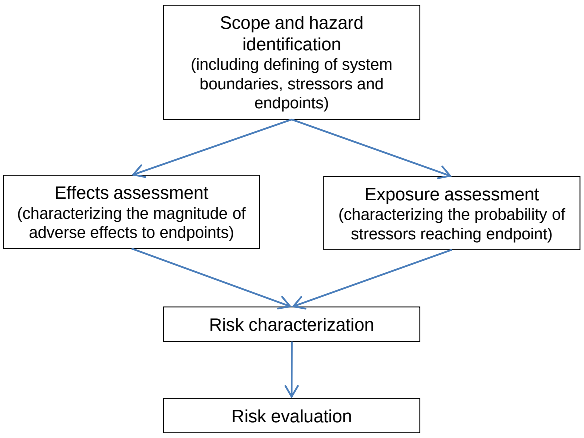

Fig. 1 Conceptual model of the procedure for EcoRA in the context of ocean energy. Modified from [10] and [11].

Risk assessment is a systematic way of estimating risk levels that emphasizes the handling of uncertainties to a higher extent than most other schools of environmental assessments. The specific EcoRA methodology refers to risks from human actions to the natural environment [12].

The EcoRA procedure is structured around stressor sources, exposure pathways and endpoints. The main steps of the procedure are [12] [13]: scope (including the definition of system boundaries and assessment endpoints), hazard identification (inventory of relevant stressors), exposure assessment (establishment of pathways and characterization of the probability of stressors reaching the endpoints), effect assessment (estimating the magnitude of effects on the endpoints), risk characterization (the product of the former two steps), and risk evaluation (the basis for decision making). Fig. 1 provides an overview of the EcoRA procedure.

Most commonly EcoRA's have been used in the context of chemical release [12] and marine applications are common [14]. The procedure of structuring links between endpoints and stressors, in turn easing both conceptual understanding of additive effects and model-based quantification of risks, may provide a feasible methodology for outlining and to some level estimating the risks from new marine activities in complex marine ecosystems, while simultaneously accounting for additive effects from co-occurring stressors.

III. Method

A hazard identification and a preliminary risk-ranking [13] based on scientific literature were carried out to inventory potential stressors and their pathways to ecological endpoints; hereby testing the applicability of the methodology and laying ground for forthcoming in-depth EcoRA. We used the ScienceDirect database [15] to identify scientific peer-reviewed articles using the search phrases "environmental impact" in combination with either "wave power", "tidal power", or "OTEC". For each of the three search combinations the first 100 articles, sorted per relevance, were browsed in order to select papers in which links (pathways) between ocean energy technologies and ecological endpoints were explained. We found 16 papers (out of 300) which describe environmental effects and specific exposure pathways (the limited number of included papers is a limitation to the study as well as it reflects a young field). From the 16 papers 94 stressor pathways of variable detail level were identified and incorporated in the analysis. The pathways were condensed and the main hazard indicators (response variables) for each endpoint were extracted. It should be noted that some of the classification of hazard indicators were inclusive; for instance the term "abundance" comprises presence, community structure, condition, and may indirectly include biodiversity.

Simple scoring [14] based on certainty and spatio-temporal magnitude of proposed effects was applied for ranking risks. Weighting values for certainty/evidence were chosen among: (1) 'qualified suggestions', (2) 'modelling or referring to effects from similar stressors', and (3) 'providing own evidence in terms of data'. Spatial range of effects was weighted as: (1) 'local effects', and (2) 'regional effects'. Temporal endurance of effects was weighted according to: (1) 'momentary during construction/decommission phase', and (2) 'persisting throughout operation phase'. For each technology and suggested pathway the ranking score was calculated as the product of the weighted values. Each exposure pathway was only scored once and where several papers described similar pathways the highest evidence value was used. The applied risk-ranking method should be understood and interpreted as the simplest way of scoring.

IV. Results

The performed hazard identification, complied in Table 1, reflects current perceptions on ecological risks from the three different ocean energy technologies. The suggested pathways are conceptually depicted in Fig. 2 and it is shown that many ecosystem components may come under exposure by the different ocean energy technologies. The risk-ranking, summarized in Table 2, indicates that wave power and tidal current power pose their highest risks to marine mammals, followed by birds and fish (including elasmobranchs). These hazards are associated with e.g. blocking of migration routes, reef-effect, collision, and electromagnetic fields. OTEC seems to pose highest risk to fish followed by plankton. Further, OTEC poses a much higher risk to eggs and larvae than other technologies. The major hazards from OTEC are associated with the risk of entrainment and impingement in in-take pipes for small fish and plankton (incl. eggs/larvae), and with the changes in water temperature and nutrient level. Alteration of pre-existing habitats and hydrodynamic conditions, inducing secondary effects on organisms, is an impact of high potency that has been suggested for all three technologies.

TABLE 1
HAZARD IDENTIFICATION FOR OCEAN ENERGY TECHNOLOGIES BASED ON IMPACTS SUGGESTED IN SCIENTIFIC LITERATURE

TE	Stressor source	Endpoints: Component	Endpoints: Indicator	Hazard and exposure pathway	EL	SR	TR
W:1 C:1 O:1	Dredging	Benthos; Corals	Abundance	Dredging causes increased turbidity and potentially release of contaminants and oxygen consuming organic matter; e.g. [16]	2	1	1
W:3 C:2 O:0	Installation activities	Benthos; Eggs and Larvae	Abundance; Recruitment	Installation of structures and cable trench remove natural seabed and increase turbidity; e.g. [17]	2	1	1
W:1 C:3 O:	Installation activities	Marine mammals; Fish	Abundance	Installation activities and vessel movements cause disturbance and pollution; [18]	2	2	1
W:1 C:1 O:0	Installation activities	Waterfowl	Migration	Installation activities and vessel movements cause avoidance and reduce food availability; e.g. [19]	2	2	1
W:3 C:3 O:1	Pile driving	Marine mammals, fish, birds	Abundance	Underwater noise causing damage, stress or avoidance; e.g. [20]	2	2	1
W:1 C:1 O:0	Sea use	Fish	Abundance	Acquisition of space prohibits fishery; e.g. [18]	1	-	-
W:2 C:0 O:0	Absorber buoy	Environment/habitat	Hydrology & biogeo-chemisty	Absorption of wave energy impose changes in physical conditions; e.g. [3]	2	1	2
W:2 C:0 O:0	Absorber buoy	Epibenthos; Algae	Coloniza-tion	Artificial structures provide additional habitat; e.g. [21]	3	1	2
W:0 C:0 O:4	Accidental leakage	Environment/habitat	Abundance	Emissions of working fluid cause toxic effects or nitrification; e.g. [22]	1	1	1
W:2 C:2 O:0	Antifouling component	Marine mammals; Environment/habitat	Abundance	Continuous release of biocides cause toxic effects; e.g. [23]	2	1	2
W:0 C:0 O:1	Discharge of mixed water	Coral; Fish; Larvae	Abundance; Recruitment	Changes in water temperature increase mortality or inhibit reproduction; e.g. [3]	2	1	2
W:0 C:0 O:4	Discharge of mixed water	Mid-water environment / habitat	Hydrology & biogeo-chemisty	Water containing chlorine, trace metals, nutrients and altered temperature changes conditions at discharge depth; e.g. [22]	2	1	2
W:0 C:0 O:4	Discharge of mixed water	Primary producers; Environment / habitat	Primary production; Hydrology & biogeo-chemisty	Artificial upwelling changes hydrological conditions in the coastal zone; e.g. [16]	2	2	2
W:4 C:2 O:1	Foundations	Algae; Epibenthos; Fish; Marine mammals; Birds	Abundance; Coloniza-tion	Artificial structures increase heterogeneity and provide additional habitat, causing reef-effect; e.g. [24]	3	1	2
W:4 C:3 O:0	Foundations	Environment / habitat	Hydrology & biogeo-chemisty	Artificial structure affects water movements and local physical conditions; e.g. [20]	2	1	2
W:3 C:0 O:0	Foundations	Marine mammals	Abundance; Migration	Artificial structure disturbs or poses risk for entanglement and functions as a barrier; e.g. [25]	2	2	2
W:1 C:1 O:0	Foundations	Waterfowl	Abundance; Migration	Artificial structure disturbs or poses risk for collision and functions as a barrier; e.g. [19]	2	2	2
W:0 C:0 O:1	Facility lights	Plankton; Fish	Abundance	Artificial light attracts or repels fauna; e.g. [16]	2	1	2

TE	Stressor source	Endpoints Component	Indicator	Hazard and exposure pathway	EL	SR	TR
W:1 C:1 O:0	Mainten-ance works	Marine mammals	Abundance	Vessel movements cause disturbance and pollution; e.g. [23]	2	1	2
W:1 C:2 O:0	Transmis-sion cables	Elasmobranchs	Foraging	Electric fields cause confusion in forage behaviour; e.g. [20]	2	1	2
W:3 C:2 O:0	Transmis-sion cables	Fish, crustaceans, turtles, mammals	Abundance; Migration	Electromagnetic fields confuse, attract, or repel; e.g. [20]	2	2	2
W:2 C:2 O:0	Turbine	Marine mammals, fish, birds	Abundance	Underwater noise may cause stress or disturbed communication; e.g. [17]	2	1	2
W:2 C:1 O:0	Turbine	Marine mammals, fish	Migration	Underwater noise from turbine disturbs orientation; e.g. [20]	1	1	2
W:0 C:4 O:0	Turbine rotor	Environment / habitat	Hydrology & biogeo-chemisty	Absorption of kinetic energy affects local currents and sediment grain size; e.g. [26]	2	2	2
W:0 C:6 O:0	Turbine rotor	Fish; Waterfowl; Marine mammals	Abundance	Fast moving rotor blade causes collision; e.g. [27]	2	1	2
W:0 C:1 O:0	Turbine rotor	Marine mammals	Migration	Fast moving rotor blade causes avoidance and altered migration; e.g. [20]	1	2	2
W:0 C:0 O:4	Surface water intake	Plankton; Egg and larvae	Abundance; Recruitment	Entrainment and exposure to low temperatures increases mortality through cold shock; e.g. [28]	3	1	2
W:0 C:0 O:3	Water intake	Plankton, fish	Abundance; Recruitment	Impingement to intake filter causes injury or increased mortality to small organisms; e.g. [22]	2	2	2
W:1 C:2 O:0	Decommis-sion	Marine mammals, fish, birds	Abundance	Extreme noise levels cause damage, stress or avoidance; e.g. [29]	2	2	1
W:1 C:1 O:0	Removal of device	Epibenthos; fish	Abundance	Removal of artificial structures reduces heterogeneity and habitats; e.g. [20]	2	1	1

Acronyms used in table:

TE Technology under assessment: **W** – Wave power, **C** – Tidal current power, **O** – Ocean thermal energy conversion. **Digits** indicate number of reviewed papers that propose the exposure pathway.
EL Evidence level of proposed exposure pathway: **1** – qualified suggestions, **2** - referring to effects of similar stressors / modelling works, **3** – providing own significant data.
SR Spatial range of effects: **1** – local, **2** – regional.
TR Temporal range of effects: **1** – momentary (during construction/decommission), **2** – persistent (during lifetime of device).

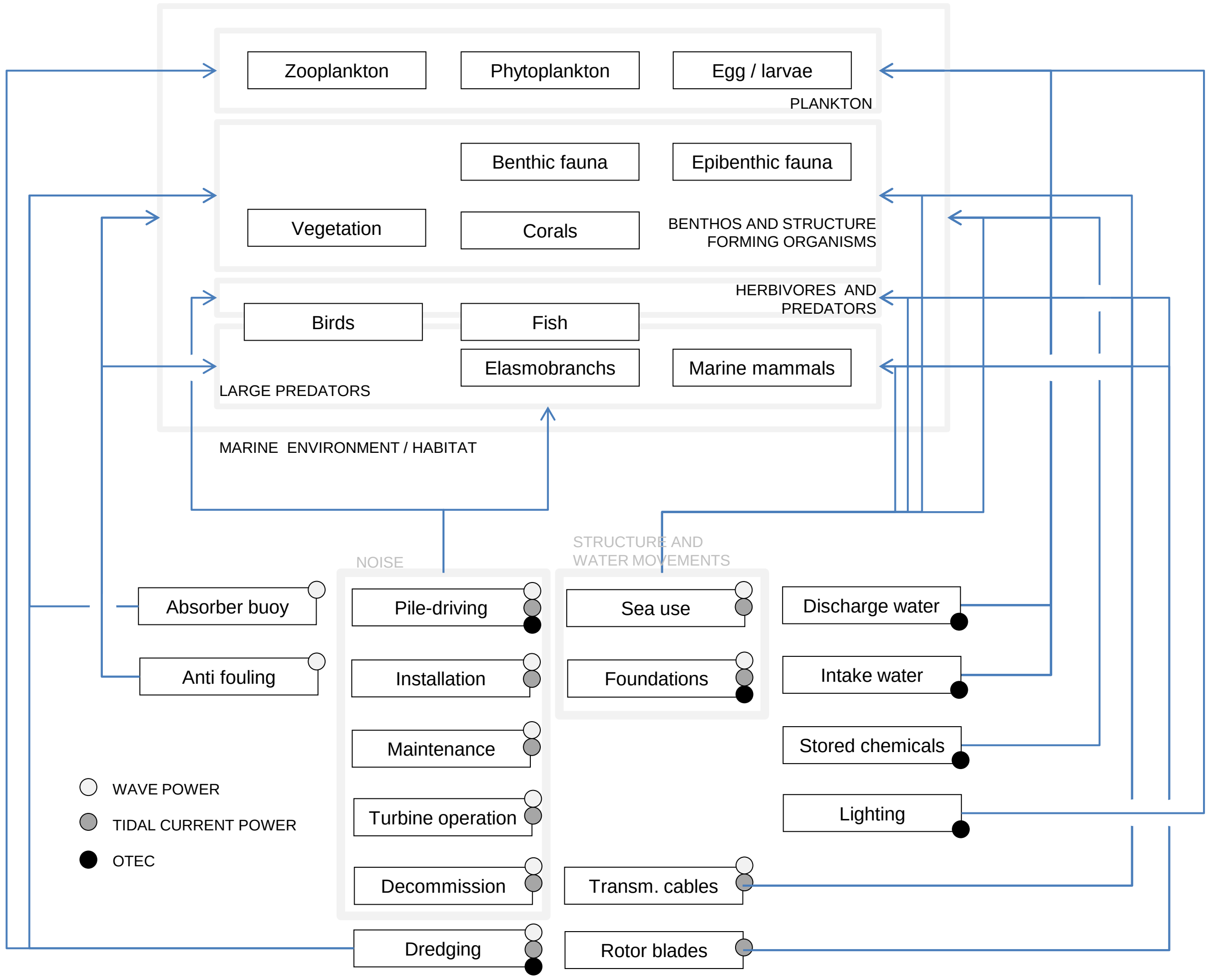

Fig. 2 Simplified conceptual model of exposure pathways between the technical system (stressor sources) and the ecological system (endpoints) according to the results of the literature search presented in Table 1.

It should be noted that most of the reviewed papers take a conservative approach when suggesting potential impacts, which means that there is a tendency to exaggerate rather than overlook risks. In some papers hazards and exposure pathways were suggested while at the same time the magnitude of impacts were thought to be of low importance (such as the effect of wave power devises on the hydrodynamic conditions [30] [31]). Further, some impacts – such as the reef-effect – may be considered positive from an environmentalist perspective, even though they imply a change to the pre-existing state of the ecosystem.

Subsequently, the results are used to discuss the applicability of EcoRA for future ecosystem-based assessments.

V. Ecological Risk Assessments of Ocean Energy

As shown by our results the number of potential endpoints is high. In risk assessments applied at the ecosystem level there is an obvious danger of "having to assess everything".

TABLE 2
Risk-ranking scores for endpoints based on the analysed material

Endpoints	Wave power	Tidal power	OTEC
Marine mammals	40	40	10
Fish (incl. elasmobr.)	22	22	26
Birds	30	30	10
Environment/habitat	12	16	13
Algae (sessile)	12	6	14
Epibenthic fauna	14	8	6
Plankton	0	0	19
Eggs / larvae	2	2	12
Electrosensitive fauna	8	8	0
Benthic fauna	4	4	2
Corals	2	2	6

As such undertaking would be impossible much effort has to be allocated to finding appropriate endpoints to address and to carefully define the system boundaries.

A. *Ecosystem-based endpoints*

It is necessary to apply suitable assessment endpoints, that is, to identify valued attributes of the environment that may be under risk. These endpoints must further be defined in operational terms. Some endpoint criteria suggested by [9] are: societal relevance (direct or indirect), biological relevance, unambiguous operational unit, accessibility for quantitative measurements and predictions, and susceptibility to the stressors in focus. While the latter three criteria are explicable, 'social relevance' would be highly dependent on the cultural context, and 'biological relevance' can be determined by its importance to higher levels of biological hierarchy [12]. When selecting operational endpoint units it should be of high importance to consider critical life-cycle events such as reproduction or migration – which implies an understanding of a whole range of meaningful spatial and temporal scales.

According to [32], important population level endpoints are abundance, production, and persistence (presence/absence) of local populations of certain species, while endpoints at ecosystem level may rather be related to changes in structural and/or functional traits. Further, it has been suggested by [12] that regional level ecosystem endpoints should be those environmental entities that affect the quality of life for (human) inhabitants in the same region. This may be interpreted as endpoints related to ecosystem services such as stabilising shallow-water vegetation, fish spawning/nursery grounds and maintenance of ecosystem productivity. To apply endpoints related to the stability of an ecosystem, as suggested by [32]; these may be interpreted as endpoints describing the resilience of an ecosystem, as has been recommended by [6] on ecosystem-based management. In practice, endpoints at the ecosystem level will give a reduced precision compared to lower level endpoints. Nevertheless, the results of this study, with its wide range of possibly affected ecosystem components, motivate an aim for "the broader picture" even though it may be at the cost of detail.

In the case of EcoRA's applied to ecosystem-based assessments of ocean energy technologies it may be relevant to start with defining valuable ecosystem components or processes at an overarching level, such as resilience in respect to maintenance of ecosystem services. Assessment endpoints can then be selected from what ensures resilience, and prevents regime shifts. Endpoints will vary with local context but may typically include predators necessary to avoid cascade effects downwards the food web, and structure-forming (or keystone) species maintaining habitats for other species or whole ecosystems [6]. The hazard identification shows that both large predators (mammals, elasmobranchs, etc.) and structure-forming endpoints (epibenthos, corals, habitat, biogeochemistry, etc.) are considered under potential risk for all three technologies (with the former category more prominent for wave- and tidal power, and the latter category more obvious for OTEC) – although the evidence is scarce. It is further shown that the hazard indicators for several endpoints have a very broad spatial range. Particularly regarding impacts on mammal migration for wave- and tidal current power, and impacts on hydrology and biogeochemistry (e.g. nutrients), which in turn affect e.g. functions related to corals and primary producers for OTEC and tidal current power. For example, it may be relevant to prioritize assessment endpoints such as marine mammal migration, nutrient levels, or coral recruitment, when selecting assessment endpoints for ocean energy EcoRA.

B. *System boundaries*

A delicate part of the formulation step of EcoRA is to establish the system boundaries of the environment under assessment. In an ecosystem-based approach, the considered system stretches across a range of spatio-temporal scales and populations tend to migrate over vast distances and interact with interlinked systems. With such a broad-scale scope the system boundaries easily become vague and difficult to define, extrapolations across spatial and temporal scales become inevitable, cumulative impacts become necessary to account for, and the number of potential endpoints increase [12].

From an ecosystem-based stand-point it would be adequate to adapt the system boundaries to the specific assessment endpoints. The hazard identification of ocean energy technologies points at temporal scales up to reproduction cycles of large predators/mammals, and spatial scales from a few hundred meters for some structure-forming endpoints to thousands of kilometres for migration-related endpoints. With the use of large system boundaries cumulative effects, i.e. the consideration of other activities affecting the same endpoint, becomes increasingly important to counteract progressive regression of ecosystem functions and ecological services.

C. *Hazard identification and exposure*

By scrutinizing the technical system (the stressor source) relevant stressors to the selected endpoints can be identified. Typical stressors are of toxicological, physical, or in some cases biological origin. Pathways between stressors and endpoints are determined by qualitative and/or quantitative methods. Weight-of-evidence (WOE) methodology is one option for the exposure and effects assessments which has been used in the case of offshore wind power [11]. Within EcoRA the most common approach to WOE has been semi-quantitative weighing of evidence lines [14].

Our analysis suggests that physical stressors are the most important hazards of ocean energy technologies (Table 1). In addition, a few toxicological stressors were suggested. Noteworthy is that only three of the reviewed papers provided "hard evidence" of effects; experimental data of increased mortality of fish eggs entrained in an OTEC warm water intake [28], and field experiments showing colonization of epibenthos and reef effect on wave power pilot plants [21] [17]. Ocean energy technologies have just recently been introduced and the lack of "hard evidence" illustrates the need for appropriate ways to handle uncertainties when transferring knowledge from adjacent fields of technologies (e.g. impacts from offshore wind power).

Stressor pathways may further pass through several trophic levels before reaching the endpoints as secondary effects. The risk of significant secondary effects through the food-web was stressed in some of the reviewed papers [20] [29] but was implicit in several others. Food-webs differ in their vulnerability to stressors [33] and it is not straightforward to quantify such complex pathways.

To choose assessment endpoints of key ecological importance ensures that the most obvious risks to altered regimes are considered. But for a thorough understanding of ecosystem risks it may be necessary to involve ecosystem modelling, e.g. [34] [35], hereby increasing quantification and transparency but not necessarily reducing uncertainties.

VI. Cumulative Effects and Significant Change

It was found that ocean energy technologies require wide system boundaries and consideration of other activities which may cause cumulative effects. Such multiple stressors may affect the endpoints by "nibbling" (different stressors with similar small incremental effects slowly decaying the endpoint), by time- or space crowded perturbations (different stressors which affect the endpoints close in time or space leaving no opportunity for recovery), and by indirect effects where the conditions of an ecosystem change until it no longer supports the original species [12].

An approach to choosing relevant multiple stressors for cumulative effects assessments is to include all other past, present or future actions that may have an effect or footprint at the chosen endpoints [36]. Another approach would be to consider all consistent effects from other stressors as an ambient condition and to keep focus on other activities with stressors which are heterogeneous in space and/or time within the applied system boundaries. Examples of relevant multiple stressors could be, for example, shark fishery and whaling regarding wave- and tidal current power; or potential coral bleaching and farmland nutrient discharge regarding risks from OTEC. We suggest that multiple stressors are incorporated in the risk assessment method, as illustrated in Fig. 3. However, to select and incorporate only those multiple stressors which are of relevance implies a challenge; more work is needed.

In the effect assessment step the fundamental difficulty is to establish how much change to the state of the endpoint represents a significant change. At an ecosystem level regime shifts (altered functionality of the ecosystem) may be an ultimate definition of significant change. But then ecosystem functionality must be efficiently measured or calculated. For particular species the crucial significant change may be related to population thresholds, which are not always straightforward to determine in advance.

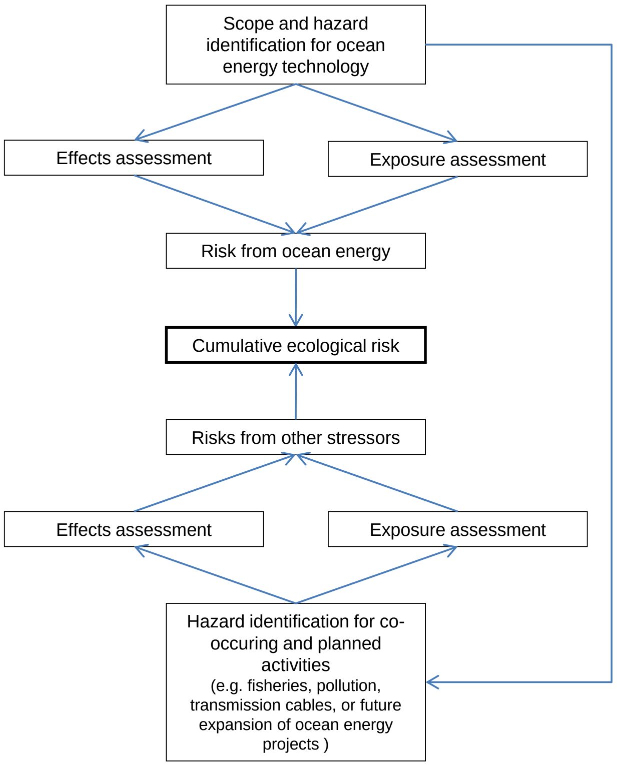

Fig. 3 The conceptual model of the EcoRA procedure may be extended to include multiple stressors, i.e. cumulative effects.

VII. Conclusions

The scientific literature-based hazard and exposure assessment indicated that all three investigated ocean energy technologies are associated with several ecological risks ranging over large spatiotemporal scales and that the level of evidence for the suggested exposure pathways are low. This has implications for the selection of endpoints and system boundaries in ecological risks assessments. In order to emphasize an ecosystem-based approach we suggest that overarching endpoints are associated with ecosystem resilience and functionality, and that multiple stressors are included in the risk model. We conclude that the EcoRA framework provides a suitable tool for structuring the complexity and uncertainties associated with ecosystem-based assessments of emerging ocean energy technologies.

REFERENCES

[1] B.D. Ferro, *Wave and tidal energy: Its Emergence and the Challenges it Faces*, Refocus, 7 (2006) 46-48.

[2] J. Khan, G.S. Bhuyan, *Ocean Energy: Global Technology Development Status*, Powertech Labs, Surrey, 2009.

[3] R. Pelc, R.M. Fujita, *Renewable energy from the ocean*, Marine Policy, 26 (2002) 471-479.

[4] R. Costananza, F. Andrade, P. Antunes, M. van den Belt, D. Boersma, D.F. Boesch, F. Catarino, S. Hanna, K. Limburg, B. Low, M. Molitor, J.G. Pereira, S. Rayner, R. Santos, J. Wilson, M. Young, *Principles for Sustainable Governance of the Oceans*, Science, 281 (1998) 198-199.

[5] B.S. Halpern, S. Walbridge, K.A. Selkoe, C.V. Kappel, F. Micheli, C. D'Agrosa, J.F. Bruno, K.S. Casey, C. Ebert, H.E. Fox, R. Fujita, D. Heinemann, H.S. Lenihan, E.M.P. Madin, M.T. Perry, E.R. Selig, M. Spaldig, R. Steneck, R. Watson, *A Global Map of Human Impact on Marine Ecosystems*, Science, 319 (2008) 948-952.

[6] L. Crowder, E. Norse, *Essential ecological insights for marine ecosystem-based management and marine spatial planning*, Marine Policy, 32 (2008) 772-778.

[7] F. Douvere, *The importance of marine spatial planning in advancing ecosystem-based sea use management*, Marine Policy, 32 (2008) 762-771.

[8] C. Ehler, F. Douvere, *Marine Spatial Planning a step-by-step approach toward ecosystem-based management*, IOC Manual and Guides, Intergovernmental Oceanographic Commission, Paris, 2009.

[9] G. Suter, L. Barnthouse, *Assessment Concepts*, in: G. Suter (Ed.) Ecological Risk Assessment, Lewis Publishers, Michigan, 1993.

[10] G. Suter, *Predictive Risk Assessment of Chemicals*, in: G. Suter (Ed.) Ecological Risk Assessment, Lewis Publishers, Michigan, 1993.

[11] J. Burger, C. Gordon, J. Lawrence, J. Newman, G. Forcey, L. Vlietstra, *Risk evaluation for federally listed (roseate tern, piping plover) or candidate (red knot) bird species in offshore waters: A first step for managing the potential impacts of wind facility development on the Atlantic Outer Continental Shelf*, Renewable Energy, 36 (2011) 338-351.

[12] G. Suter, *Defining the Field*, in: G. Suter (Ed.) Ecological Risk Assessment, Lewis Publishers, Michigan, 1993.

[13] M. Burgman, *Risks and Decisions for Conservation and Environmental Management*, Cambridge University Press, Cambridge, 2005.

[14] I. Linkov, D. Loney, S. Cormier, F.K. Satterstrom, T. Bridges, *Weight-of-evidence evaluation in environmental assessment: Review of qualitative and quantitative approaches*, Science of The Total Environment, 407 (2009) 5199-5205.

[15] (2011) SciVerse, ScienceDirect [online]. Available at: http://www.sciencedirect.com/

[16] M.S. Quinby-Hunt, D. Sloan, P. Wilde, *Potential environmental impacts of closed-cycle ocean thermal energy conversion*, Environmental Impact Assessment Review, 7 (1987) 169-198.

[17] O. Langhamer, *Effects of wave energy converters on the surrounding soft-bottom macrofauna (west coast of Sweden)*, Marine Environmental Research, 69 (2010) 374-381.

[18] Z. Defne, K.A. Haas, H.M. Fritz, *GIS based multi-criteria assessment of tidal stream power potential: A case study for Georgia, USA*, Renewable and Sustainable Energy Reviews, 15 (2011) 2310-2321.

[19] R. Langton, I.M. Davies, B.E. Scott, *Seabird conservation and tidal stream and wave power generation: Information needs for predicting and managing potential impacts*, Marine Policy, 35 (2011) 623-630.

[20] A.B. Gill, *Offshore renewable energy: ecological implications of generating electricity in the coastal zone*, Journal of Applied Ecology, 42 (2005) 605-615.

[21] O. Langhamer, D. Wilhelmsson, J. Engström, *Artificial reef effect and fouling impacts on offshore wave power foundations and buoys - a pilot study*, Estuarine, Coastal and Shelf Science, 82 (2009) 426-432.

[22] S.A. Abbasi, N. Abbasi, *The likely adverse environmental impacts of renewable energy sources*, Applied Energy, 65 (2000) 121-144.

[23] S. Dolman, M. Simmonds, *Towards best environmental practice for cetacean conservation in developing Scotland's marine renewable energy*, Marine Policy, 34 (2010) 1021-1027.

[24] P.K. Probert, R. Mitchell, *Environmental Implications of Wave Energy Proposals for the Outer Hebrides and Moray Firth*, Ocean Engineering, 10 (1983) 459-469.

[25] O. Langhamer, K. Haikonen, J. Sundberg, *Wave power--Sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters*, Renewable and Sustainable Energy Reviews, 14 (2010) 1329-1335.

[26] S.P. Neill, E.J. Litt, S.J. Couch, A.G. Davies, *The impact of tidal stream turbines on large-scale sediment dynamics*, Renewable Energy, 34 (2009) 2803-2812.

[27] P. Breeze, *Ocean power*, in: Power Generation Technologies, Newnes, Oxford, 2005, pp. 204-218.

[28] Y. Lamadrid-Rose, G.W. Boehlert, *Effects of cold shock on egg, larval, and juvenile stages of tropical fishes: Potential impacts of ocean thermal energy conversion*, Marine Environmental Research, 25 (1988) 175-193.

[29] M.A. Shields, L.J. Dillon, D.K. Woolf, A.T. Ford, *Strategic priorities for assessing ecological impacts of marine renewable energy devices in the Pentland Firth (Scotland, UK)*, Marine Policy, 33 (2009) 635-642.

[30] D.L. Millar, H.C.M. Smith, D.E. Reeve, *Modelling analysis of the sensitivity of shoreline change to a wave farm*, Ocean Engineering, 34 (2007) 884-901.

[31] A. Palha, L. Mendes, C.J. Fortes, A. Brito-Melo, A. Sarmento, *The impact of wave energy farms in the shoreline wave climate: Portuguese pilot zone case study using Pelamis energy wave devices*, Renewable Energy, 35 (2010) 62-77.

[32] G. Suter, S. Bartell, *Ecosystem-level Effects*, in: G. Suter (Ed.) Ecological Risk Assessment, Lewis Publishers, Michigan, 1993.

[33] H.J. De Lange, J. Lahr, J.J.C. Van der Pol, J.H. Faber, *Ecological Vulnerability in Wildlife: Application of a Species-Ranking Method to Food Chains and Habitats*, Environmental Toxicology and Chemistry, 29 (2010) 2875-2880.

[34] P.J. Sydelko, I. Hlohowskyj, K. Majerus, J. Christiansen, J. Dolph, *An object-oriented framework for dynamic ecosystem modeling: application for integrated risk assessment*, The Science of The Total Environment, 274 (2001) 271-281.

[35] G. Holmes, R.W. Johnstone, *Modelling coral reef ecosystems with limited observational data*, Ecological Modelling, 221 (2010) 1173-1183.

[36] G. Hegermann, C. Cocklin, R. Creasey, S. Dupois, A. Kennedy, L. Kingsley, W. Ross, H. Spaling, D. Stalker, *Cumulative Effects Assessment Practitioners Guide*, AXYS Environmental Consulting Ltd. and the CEA Working Group for the Canadian Environmental Assessment Agency, Hull, 1999.