海上风电对海洋生态环境与海洋生物资源的综合影响研究进展

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摘要: 海上风电具有就近消纳方便、发电效率高和不消耗化石能源等特点, 在低碳经济发展背景下, 加快海上风电开发已成为全球各国促进能源结构转型与可持续发展的普遍共识。但海上风电在建设及运营过程中所产生的噪音和磁场对海洋环境和生物的影响尚不明确。本文系统梳理了全球海上风电发展现状, 分析了海上风电开发对海洋生态环境与生物资源的综合影响, 从生理、行为和分子三个层面重点分析了海上风电所产生的噪音和磁场对海洋生物的潜在影响, 以期为科学利用海上风电提供参考。

关键词: 海上风电; 环境影响; 噪音; 电磁效应; 生态效应

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在低碳经济背景下, 加速能源结构的清洁化转型得到了世界各国的普遍重视[1]。清洁能源是指能源在生产和消费的过程中对环境影响较小且污染风险极小的能源类型, 主要包括风能、水能、太阳能、地热能和海洋能等[2]。近年来, 风力发电作为典型的清洁能源, 在全球范围内迅速发展[3]。据国际可再生能源署(IRENA)数据表明, 2020 年全球能源投资为 3 830 亿美元, 其中风能投资占全球能源投资的 37.3%, 总金额高达 1 428.59 亿美元[4]。

与陆地相比, 海洋风力资源更为丰富。海上风电发电效率比陆地高 50%, 年平均使用时间高达 2 500 h, 开发价值和利用潜能更高[5]。全球海上风电开发以丹麦研发安装的第一台海上风力涡轮机为起点, 历经了初始研究阶段(1980—1990)、实验测试阶段(1991—2000)和商业化阶段(2001 至今)3 个关键时期[6]。自 2001 年海上风电大规模产业化技术实现突破以来, 全球海上风电装机容量以 20%的速度出现连年增长。当前, 全球海上风电建设主要集中在英国、荷兰、丹麦等欧洲各国, 累计装机占比高达 75%, 其次为亚洲和北美洲[7]。

我国海上风电资源十分丰富, 且我国电力负荷中心位于东部沿海地区, 具有就地消纳便捷的优势, 发展海上风电可减小火电压力, 为保障电力稳定供应提供重要支持[8-9]。与欧美不同, 我国海上风电开发主要集中于潮间带或浅海区域, 开发成本和技术难度远低于深海风电开发, 因此近年来装机规模快速增长[10]。根据国家能源局统计数据, 截至 2021 年 4 月底, 我国海上风电并网容量达到 1 042 万千瓦, 已连续 3 年高居全球新增装机容量最多的国家, 正成为全球海上风电产业发展的新中心。

在“十四五”期间, 海上风电作为我国实施能源安全新战略的重要环节, 落实碳达峰、碳中和目标的重要落脚点, 发展前景更为广阔。可积极推动我国海上风电在近海规模化发展、远海示范化发展的战略布局, 实现海上风电“近海—远海”协同发展的新局面。

然而, 海上风电的开发全过程可能会对海洋生态造成一定的潜在影响[11]。例如, 在建设阶段, 海底工程作业会产生废弃污染物, 风机安装过程中会产生强噪音引起鱼类出现应激反应[12-13], 海底电缆的

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铺设可能会改变海底原有地形地貌[14]，导致底栖生物栖息环境丧失或退化；在运营阶段，风机机组会产生低频噪音和电磁辐射等可能会对海洋生物造成慢性影响，而风机叶片转动可能会误撞鸟类，影响鸟类迁徙等[15-18]。目前我国正处于海上风电建设增长的关键期，尤其是提出了将海上风电和海洋牧场的融合发展的全新理念，在“绿水青山就是金山银山”根本前提下，全面了解海上风电对海洋生态环境和海洋生物资源的综合影响具有重要的研究意义与产业价值[19]。

1　海上风电的资源环境效应

海上风电产生的资源环境效应是指风机基础的淹没部分可起到人工鱼礁的作用，可为生物增殖提供栖息地，增加该区域的生物资源量和多样性[20-23]。在德国湾 5 000 个海上风电机组规模下，沉积物中生物量与最初相比预计可增加 4 000 倍[24]。De Mesel 等[25]调查了在比利时北海建造的 C-power 海上风电场，并分析了风机基础上的附着生物群落演替，演替第一年，有大量新物种殖民迁入，附着贝类迅速繁殖，随后能够吸引 20 多种迁移性生物来此提升该区域的生物多样性。Stenberg 等[26]对丹麦 Horns Rev 1 海上风电场进行了 10 年(2001—2010)的长期跟踪调查，发现底栖生物及游泳动物数量保持了基本稳定，但生物多样性明显提升；Leonhard 等[27]发现该海上风电场鱼类和其他生物的食物供应增加了 50 倍，能够吸引诱集恋礁型生物到此处繁殖，进而在风机基础周围发挥人工礁效应。Lindeboom 等[28]通过对荷兰 Egmond aan Zee 海上风电场进行了 5 年(2004—2009)跟踪调查，发现风机基础及四周覆石区聚集了更多生物，舌鳎、鳕鱼等鱼类数量显著提升。类似的现象在德国 Bight、瑞典 Lillgrund 海上风电场也有报道[29-30]。

除长期的跟踪调查外，Ecopath with Ecosim(EwE)等生态模型也被用来预测海上风电场建设后的物种多样性变化。例如，Wang 等[31]分析发现了江苏如东风电场建设后风电场内浮游动植物、部分底栖生物及鱼类等物种的丰度和生物量均呈增加的趋势。Raoux 等[32]对英吉利海峡内的 Courseulles-sur-mer 海上风电场进行模拟预测，结果表明 30 年后海上风电场系统内总生物量将增加 55%，主要原因是海上风电场建成后，系统内物质循环率提升，高营养级生物向风电场区域迁移。以上结果表明，风机基础可以作为一种潜在人工礁以达到吸引鱼群的目的[33-34]。此外，德国等国家在海上风电区域开展生态渔业[35]，对海洋资源的修复和养护起到的作用更加明显[36]。海上风电作为我国大力发展的产业之一，具有海洋生物资源养护作用，能够较好地固碳增汇，未来可以与海洋牧场融合发展扩大其资源环境效应的发挥。

2　海上风电的潜在负面效应

海上风电开发规模较大，其建设、运营、退役各个阶段都可能会对海洋生态环境与生物资源产生潜在负面影响，系统客观地掌握并评估海上风电开发对其影响的研究进展，对促进海上风电开发建设有指导作用。

2.1　海上风电的潜在负面影响因素

海上风电的潜在负面影响通常包括开发过程中对沉积环境的扰动、产生物理能量的排放和对鸟类的视觉干扰等[37]。海上风电选址通常是细沙沉积物区，其建设过程会改变海底地形地貌，风机基础打桩钻探及海底电缆铺设都会对海洋沉积环境造成一定的破坏[38]，导致海底水体浊度上升，溶解氧降低，对海洋生物造成缺氧等影响。风机基础的防腐装置还会产生重金属析出等[39]。此外，风机基础建设会造成海底基质硬化[40]，导致部分底栖生物的生境丧失及恶化，生物多样性下降。海上风电场建成后，海流经过风机基础时，会产生湍流作用并持续冲刷桩基下方的沉积物，导致桩基迎水面及其后方主要呈现淤积趋势，而两侧呈现冲刷趋势，在海底电缆附近也发现一定程度的海床侵蚀[41-42]。张晶磊[43]以情景分析法为框架，运用 GIS 技术和数学模型，对我国江苏滨海海上风电工程开发进行环境累积影响评价。结果表明：随着海上风电建设区域的扩增，海水污染因子超标率增加，浮游生物及底栖生物产生一定的损失，其累积影响会随着建设规模的扩大而增加。

海上风电建设及运营过程会产生噪音、电磁辐射和桩基振动等物理能量的排放[44-46]。其中，噪音会导致海洋声景发生改变，海上风电建设打桩噪音约 226 dB re 1μPa，距离打桩点 80 km 才降至背景噪音水平[47]；运营噪音约为 120~140 dB re 1μPa，频率为 1 kHz 以内，与风速、风机类型密切相关，且风机排列具有一定距离，因此噪音的累加效应尚不明确。但在风机周围，会对石首鱼科等声音敏感的生物造成

影响[48-51]。海上风电运营期间，海底电缆的电力传输会产生电磁场[46]，产生磁场强度在 110~3 200 μT 的极低频电磁场[52]。同时也可能使该区域磁场倾角发生改变，进而对鳗鱼等依靠地磁场导航的生物会造成一定影响[53-54]。运营中的海上风电是一个长期存在的振动源[55], Lin 等[56]通过不同频率的水下振动实验，研究了桩基振动对仿刺参(*Apostichopus japonicus*)运动行为的影响，结果发现高频率的振动可能会诱发刺参出现的规避行为。

海上风电也会对鸟类产生一定影响，具体表现为风机转动会对鸟类形成视觉干扰[57]，而磁场的改变又会对依靠地磁场导航的鸟类造成影响[58]，但与陆地风电场经常发生的鸟类、蝙蝠和风机叶片发生的碰撞事件相比[59]，国内外研究普遍认为海上风电场对鸟类的影响较小，仅发生在海鸟迁徙期间，“鸟撞”事件发生概率较低[60]。

2.2　海上风电噪音对海洋生物的影响

噪音存在于海上风电开发的整个过程[61]。建设期产生的打桩声，声级最高，为急性噪音[62-63]；运营期的噪音具有累积性，影响更为长久[64]。噪音会产生声学干扰，掩蔽声学交流[65]，进而改变白鲸等的海洋生物的行为模式，并影响海洋生物的生理状况等，严重时还会对其生命造成威胁。

2.2.1　海上风电噪音对海洋生物行为模式的影响

噪音会对海洋生物的行为造成影响，且在不同生物中行为响应差异较大[66]。急性噪音会导致海洋生物出现应激行为，长期暴露于噪音环境中则会导致其听觉系统发生改变，削弱其感受环境的能力[67-69]。

噪音对海洋生物行为的影响具体表现为埋栖行为、集群行为、捕食行为、求偶行为等发生改变。例如，噪音会影响缢蛏(*Sinonovacula constricta*)的埋栖行为，高强度的噪音会导致其埋栖更深，原因为缢蛏(*S. constricta*)为了缓冲声波产生的粒子振动干扰而深埋泥沙中[70]。斑马鱼(*Danio rerio*)在噪音暴露下会出现明显的行为改变，具体表现游泳速度短暂增大，个体间分散距离变大，进而对集群行为产生干扰[71]。噪音对鱼类的捕食行为影响研究较多。例如，噪音干扰导致欧洲鳗鲡(*Anguilla anguilla*)侧化行为变弱，反捕食性能降低[72]，打桩噪音会导致长鳍近海鱿鱼(*Doryteuthis pealeii*)的捕食效率降低[73]，同时也会对其警报行为造成干扰[74]，而三刺鱼(*Gasterosteus aculeatus*)在风电噪音回放暴露下，会出现捕食误差增加，捕食效率降低等[75]。此外，在噪音暴露后，双斑虾虎鱼(*Gobiusculus flavescens*)和彩绘虾虎鱼(*Pomatoschistus pictus*)均会出现雄鱼视觉、听觉求爱行为降低，雌鱼产卵率降低的现象，进而对该物种的种群数量造成一定影响[76]。

噪音对哺乳动物危害最为严重，大部分海洋哺乳动物对声音比较敏感[47, 77]。在苏格兰 Moray Firth 海域海上风电打桩近点处拟合打桩噪音水下衰减曲线，通过和宽吻海豚(*Tursiops truncatus*)的声学特性曲线对比，发现在距离打桩 5 m 处宽吻海豚(*T. truncatus*)会出现听觉永久性损伤，在 10 m 处会出现短暂的听力缺失[78]。此外，海洋哺乳动物多通过声音进行种间交流，因此运营期的海上风电可能会对种间交流造成掩蔽效应[79]。但是，与观察到结果不同的是，目前全球海上风电场附近有海洋哺乳动物分布和活动的观测报道，原因可能为风机基础产生的增殖效应和保护地效应，对大型哺乳动物具有较强吸引和保护作用[32]。但具体机制有待研究。

2.2.2　海上风电噪音对海洋生物生理状态的影响

海上风电建设对海洋生物生理的影响主要表现在应激生理方面，并存在明显的时间效应[80]。例如，在鱼类中，大吻异线鳚(*Heterostichus rostratus*)在高声压级的间歇噪音中应激反应最为强烈[81]。在初期噪音暴露中，尼罗罗非鱼(*Oreochromis niloticus*)表现出高呼吸频率，但暴露超过 120 天后，应激反应趋于缓和并表现出正常的生理状态[82]。大西洋鳕鱼(*Gadus morhua*)和青鳕鱼(*Pollachius virens*)都会在反复的噪音暴露试验中表现出逐渐适应状态[80]。而皮质醇是反应噪音对鱼类应激生理的关键指标[81, 83]。

在双壳贝类中，研究多集中在生物大分子酶的活性方面。例如，缢蛏(*S. constricta*)在强噪音下会出现代谢酶活性下降，新陈代谢降低[70]，高频噪声对地中海蓝贻贝(*Mytilus galloprovincialis*)消化腺生理有负面影响[84]。此外，噪音会加剧重金属对贝类的毒性效应，例如泥蚶(*Tegillarca granosa*)在 70~100 dB 的噪音下会通过协同作用增强对 Cd 的富集[85]。

2.2.3　海上风电噪音对海洋生物影响的分子机制

风电噪音对海洋生物影响的分子机制解析研究极少，仅在贝类中有相关报道。例如，当缢蛏(*S. constricta*)暴露于噪音时，其糖酵解、脂肪酸合成、色氨酸代谢和三羧酸循环等 10 个相关代谢基因的表达发生改变，在 80 dB re 1μPa 的噪音环境下，相关基因均被诱导表达升高，在 100 dB re 1μPa 的噪音环

境下，相关基因均被抑制表达[70]。Shi 等将泥蚶(*T. granosa*)暴露在 Cd 和人为噪音下，发现其与神经递质分泌的相关基因(MAO、AChE 和 mAChR3)表达显著下调，表明暴露于噪音污染可以抑制其神经递质分泌，进而通过协同效应加强了 Cd 对泥蚶(*T. granosa*)的毒理影响作用影响[85]。

2.3 海上风电磁场对海洋生物的影响

海洋环境中存在自然地磁场，海鸥等许多电磁感生物依靠地磁场进行导航迁移[54, 86]。而海上风电中风机、升压站、海底电缆均会产生额外的电磁场[87]，但由于不同介质间电磁辐射衰减较快，因此位于海平面上方的风机和升压站所产生的磁场对海洋生物影响很小，海上风电的电磁辐射主要来源于海底电缆，而最可能受到海底电缆电磁场影响的海洋生物通常为运动能力较弱的底栖生物[88-89]。

2.3.1 海上风电磁场对海洋生物行为模式的影响

磁场对不同海洋生物行为的影响差异极大，相关研究多集中于甲壳类动物。例如，南极沙蚤(*Gondogeneia antarctica*)在 20 nT 及以下的极低频电磁场暴露 1 min 后会迷失方向[90]，而欧洲螯龙虾(*Homarus gammarus*)在 200 μT 磁场内行为模式未发现明显改变[91]，但食用黄道蟹(*C. pagurus*)却表现出明显的趋磁行为[92]。此外，当沙蚕(*Hediste diversicolor*)暴露于磁场干扰后，其掘洞行为出现显著加强，但磁场对海洋动物行为的影响机制仍未得到明确的解析[93]。

2.3.2 海上风电磁场对海洋生物生理状态的影响

磁场对海洋生物生理影响的野外调查极少，多在实验室开展模拟实验。沙蚕(*H. diversicolor*)暴露于海底电缆典型磁场后，排氨率出现显著降低[93]。食用黄道蟹(*C. pagurus*)暴露于磁场后，会出现 L-乳酸盐和 D-葡萄糖的昼夜代谢生理紊乱[92]。磁场对鱼类胚胎发育影响较为复杂，例如，虹鳟(*Oncorhynchus mykiss*)受精卵放置在电磁场(50 Hz, 1 mT)内，其存活率未发生显著降低，但卵黄的吸收率出现显著上升[89]，类似的结果在白斑狗鱼(*Esox lucius*)中也有报道，原因为磁场暴露加快了生物的代谢率[94]。但斑马鱼(*D. rerio*)在磁场干扰下，孵化周期却出现了显著延迟[95]。在棘皮动物中，研究也发现磁场暴露下紫海胆(*Paracentrotus lividus*)胚胎细胞的有丝分裂受到扰乱，进而影响正常的分裂与发育[96]。因此，当海底电缆释放的电磁场为 1 mT 或更高时，在相应范围内的生物会受到潜在影响[97]。

2.3.3 海上风电磁场对海洋生物影响的分子机制

电磁场暴露对海洋生物影响的分子机制的研究也较少，且多集中在转录水平。例如，Zhang 等[98]采用转录组测序技术，发现瘤背石磺(*Onchidium struma*)为在极低频磁场(50 Hz, 100~500 μT)中暴露一周后可诱导免疫应答，而地中海蓝贻贝(*M. galloprovincialis*)在低频电磁场(50 Hz, 400 μT)中，热休克蛋白 HSP70 和 HSP90 的表达出现上升[99-100]。在细胞水平，当虹鳟(*O. mykiss*)、蛤蜊(*Limecola balthica*)和沙蚕(*H. diversicolor*)暴露于电磁场时，受试生物均不同程度的出现了微核等染色体畸变等异常现象，表明电磁场会导致海洋生物染色体的结构畸变并对遗传产生进一步的影响[93]。但值得注意的是，相关研究多集中于室内模拟环境，在海上风电场中单个海洋可再生能源设备或小阵列电缆所产生的电磁辐射的生态影响是有限的[101-102]，因此野外调查和现场研究亟待开展。

3 研究展望

海洋生态系统是一个动态系统，海上风电使海洋资源利用多重化、海洋空间碎片化，目前我国海上风电建设方兴未艾，发展海上风电的同时更需关注其生态影响。本文系统总结了海上风电对海洋生态环境和生物资源的综合影响。然而，因海上风电对海洋生态环境的影响较为复杂，需要详细的野外调查研究来进一步明确其作用机制。此外，在刚性环保要求下，环保型海上风电机组装备研制、生态型海洋牧场与海上风电融合发展模式创制，也是我国未来高效、生态开发利用海上风电资源的重要举措之一。

3.1 环保型海上风电机组装备研发

研制低噪音海上风电机组装备，通过集成优化风机叶片形态设计、风机叶尖降噪装置、风机发电机组降噪设计，有效减少海洋哺乳动物、海洋鱼类等敏感的低频噪音产生；研发海上风机绿色防腐技术，通过新型海洋防腐涂料的使用，减少锌、铝等牺牲阳极材料的使用，进而有效减少风机基础重金属的析出污染，并制定环保型海上风机组件的选材、制造与安装标准化技术体系，以标准化保障海上风电的绿色建设和生态安全。

3.2 海上风电精准选址和优化布局

研发海上风电场精准规划与选址技术，采用高

精度声学和遥感等观测装备，保障海上风电场与鱼类洄游路线和产卵育幼场、鸟类栖停迁飞路线、海洋哺乳动物领地等生态红线区域不冲突；创制海上风电场优化布局技术，保障风机基础的精准投放安装，实现风机机组周年运行稳定，提高海上风电的开发利用效率，保障海上风机机组的年发电量，通过海上风电场的精准选址和优化布局，在保障海洋生物生态安全的基础上，实现海上风电资源的高效开发。

3.3 海上风电生物立体监测和作用机制解析

建立海上风电区域资源环境立体监测和实时生态安全网络预警体系，集成水下多环境因子、水下鱼类和哺乳动物视频采集、水上鸟类视频采集、大数据集成传输分析技术的应用，实现对海上风电场区域生态安全的实时监测并及时预警预报；针对海上风电运营期噪音、磁场对海洋生物影响机理不清、机制不明的研究现状，以我国海域常见物种为研究对象，从行为、生理、分子角度开展系统研究，全面阐明海上风电对海洋生物生存繁殖的综合影响，为大规模开展海上风电建设提供理论指导。

3.4 海上风电与海洋牧场融合发展模式创制

海上风电是实现“双碳”目标的重要抓手，海上风电与海洋牧场融合发展新模式是实现科学、集约、生态用海的重要途径。研制资源增殖型风机基础，充分发挥风机基础的人工鱼礁效应，增殖养护附着性贝类和仔稚鱼等资源；并利用风电场内空置海域，创制风机基础与智能网箱、筏架、鱼礁等海洋牧场典型构建设施的有机融合模式，在生产清洁能源的同时，高效产出优质水产蛋白，实现海上风电与海洋牧场的协同发展。

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Research progress on the comprehensive impact of offshore wind farms on the marine ecological environment and biological resources

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Abstract: Offshore wind farms exhibit the characteristics of convenient consumption nearby, high energy generation efficiency and no consumption of fossil energy. In the background of low-carbon economic development, accelerating the growth of offshore wind farms has become a consensus for several countries around the world to promote the transformation and sustainable development of energy infrastructure. However, the impact of noise and magnetic fields generated by such wind farms on the marine environment and organisms remains unclear. This paper systematically reviews the current situation of global offshore wind farm development, analyzes its comprehensive impact on the marine environment and biological resources, and summarizes the potential effects of the noise and magnetic field generated by these wind farms on marine organisms from the physiological, behavioral, and molecular perspectives, thus providing a reference for scientific research on offshore wind farms.

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