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The role of technology and digital innovation in sustainability and decarbonization of the Blue Economy

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The development of a sustainable technology for the Blue Economy (a new Blue Technology) sets out three core research objectives, reflecting key challenges to be tackled by the sea industries and scientific and technological communities: The fast development of doable decarbonization processes through development and demonstration of deployable, competitive, and sustainable technological solutions for energy transition (climate neutral blue economy), a sustainable exploitation and exploration of oceans, seas and coastal areas to provide new resources, from raw materials to products, including food (sustainable use and management of marine resources), and the development and exploitation of digital-based knowledge while accumulating data from new observation networks (persistent monitoring and digitalization of seas and oceans).

To meet these operational objectives, different topics and related technologies need to be further developed. A possible list of disciplinary objectives is the following.

1. Climate neutral blue economy

Sustainable solutions for energy transition and decarbonization processes are already technologically possible in many fields of the blue economy. An example is the Ocean Energy, which is relevant for the achievement of the energy transition objectives towards low carbon emission sources (e.g., EWTEC, 2019). New power plants should be designed while paying attention also to the protection of biodiversity, thus favouring the adoption of an ecosystem approach. Sea industries must improve technologies and devices for the production, storage, and distribution of energy and for the integration of different forms of renewable energy (wind-tidal-wave), including advanced artificial intelligence (AI) tools for intelligent smart grids. The methodologies for the choice of installation sites should also be improved by introducing measures to mitigate the impact of the structures on the marine environment and the invasiveness of probing strategies for site selection (Bui et al., 2018, Coro and Trumpy, 2020). The design of new production plants should include the evaluation of end-of-life effects on the marine environment. It is also fundamental to advance the efficiency of the storage systems as a major factor leading towards greater energy system integration of renewable energies.

In addition to increasing renewable energy and promoting energy efficiency and conservation, capturing and storing CO_2 is a cost-competitive and safe way to achieve large-scale reductions in emissions (Bui et al., 2018). A complete carbon capture and storage system (CCS) relies on three technological components: capture, transport, and storage. Capture technologies can be divided into post-combustion, pre-combustion and oxyfuel combustion. Once the CO_2 is separated and captured, it must be compressed to reduce the volume of gas for transportation to an appropriate storage location. Ships are cost-effective only if the CO_2 must be moved more than 1,000 miles away. It is possible to store CO_2 in the ocean, but public opposition to the idea of injecting CO_2 directly into the deep ocean has prevented some research on this option, despite the ocean's natural capacity to store most of the CO_2 currently emitted into the atmosphere.

2. Sustainable use and management of marine resources

Sustainable decommissioning and conversion of offshore platforms has recently attracted great interest and represents a great opportunity for the enhancement of marine resources (OECD, 2019). Each option determines environmental and socio-economic impacts that must be considered in the conversion process, which overall calls for identifying and investigating scenarios of possible alternative solutions. Attention must be focused on developing models for the analysis and evaluation of decommissioning projects that include the main environmental sustainability parameters, while identifying new materials and technologies for the design and construction of platforms that consider also their end of life. Efficient and sustainable technologies for maintenance and intelligent monitoring of platforms, and predictive methods for knowing their status and the decommissioning risks will benefit from the use of sensor development, AI, and Digital Twin technologies.

Understanding the ecosystems in which aquaculture plants operate, in terms of abiotic variables (e.g. currents, thermo-salinity, etc.) and biological variables (from productivity to the natural recycling of elements), represents a fundamental research objective in the sector (OECD, 2019). Technological innovation must aim, above all, at reducing the environmental impacts of existing aquafarms, while improving their maintenance and operativity through intelligent autonomous vessels, and ICT systems. Dedicated ecosystems modelling that considers plant location characteristics and environmental impacts and costs is necessary in this context.

The seabed of the oceans is largely unexplored. Preliminary explorations have revealed the presence of raw materials essential for the green economy (e.g. polymetallic nodules, sulphides, cobalt-rich ferromanganese crusts, methane hydrates), in concentrations generally much higher than on land, that may represent - in the future - a solution to the increasing demand for mineral resources and supply risks. In this context, preliminary seabed mining activities have already started. However, the current technology is primitive, and the devices designated to collect and analyse these resources have the potential to annihilate the marine ecosystem of the seabed, which must still be studied and understood (Barbier et al., 2014). This is one of the most critical points of the entire sustainable blue economy. The research roadmap should include the development of sustainable exploration devices, with minimum (and reversible) environmental impacts (e.g. dedicated new autonomous underwater vehicles capable of reducing sediment removal, new underwater communication systems, intelligent strategies for exploration, etc.).

The coexistence of multiple economic activities needs to be carefully planned to avoid conflicts and promote synergies while preserving the marine ecosystem. Therefore, the full development of Maritime Spatial Planning (MSP) is urgent to implement a sustainable sea and ocean blue economy, which requires a multidisciplinary effort to create new supporting tools that can integrate many different aspects and disciplines, including socio-economic and political factors (Zaucha and Gee, 2019).

Maritime Surveillance – i.e. the protection of marine resources (illegal fishery control, oil spill detection, environmental degradation monitoring, etc.), food security, transport safety and the monitoring of critical marine infrastructures (renewable energy and aquaculture offshore platforms) - is key for a sustainable growth. Different observation systems for data acquisition (satellite, in situ, AUV, social media, etc.), data sharing and management are the fundamental tools for Maritime Surveillance. Integration platforms and services through data sharing between the existing EU and national platforms will have to be developed, together with platforms allowing Big Data Analytics and social sensing data integration (Claramunt et al., 2017).

3. Developing “blue technology” for the sustainable “blue economy”

New advanced technologies are becoming available at an unprecedented speed. A non-exhaustive view of all emerging technologies which focusses on the technologies that are favourable to collaborative research within the Blue Growth context might be the following:

- **Marine Robotics:** Remotely Operated Vehicles (ROVs) and Autonomous surface/underwater vehicles (ASVs, AUVs) are used to perform missions that cannot be easily accomplished by other marine vehicles or by humans because of the costs, the harsh environment, or because they involve risky operations (surface and underwater observation and monitoring, SAR, deployment, inspection, maintenance and recovery of structures, identification of mines and unexploded ordnance). The goal is to improve endurance and navigation for extended exploration, improve hoovering stability for high-resolution imagine analysis and automatic identification of objects/species also using AI approaches, lower the acoustic signature for underwater noise minimization, introduce solutions using swarms of small, low-cost, single task, easily deployable autonomous vehicles.

- **Advanced Materials and Manufacturing:** New materials and developments in material technology are fundamental to meet new environmental regulations, operate in adverse environmental conditions (e.g. deep-sea operations) and improve the capabilities and performance of marine robots. Possible applications regard deep-sea technology, soft robotics, nature-based solutions for offshore infrastructures, smart and intelligent materials for structural monitoring, energy harvesting and storage.
- **Advanced computational methods**: modelling and simulation are becoming increasingly powerful tools because of hardware and algorithmic constant improvement, which also allows for assimilating past and new data with physics-based computational models. New computational capabilities will enable the development of advanced modelling and simulation tools for the design and optimization of new marine energy plants, and the introduction of tools to observe, monitor, and simulate marine environment dynamics, and for virtual prototyping and next-generation energy management.
- **Sensors are Everywhere**: Advances in material technology is allowing the reduction of the cost and size of sensors, while fostering their ubiquitous incorporation into a wide range of inexpensive objects. In medium-to-long terms, every object will be a potential source of sensor data. Advanced computational techniques to integrate sensor data will lead to the possibility to sense the environment as well as the anthropogenic impact at significantly greater ranges and with a richer context than what is currently possible. In this context, it will be fundamental to develop specific biochemical sensors for monitoring contaminants at low concentrations, and in general to estimate the environmental status.
- **Tools for digital transition**:
  - **Everywhere computing**: Technology is rapidly connecting devices to each other, to benefit from distributed data structures and cloud computing services. Everywhere computing also encompasses software-driven functionality, the ability to process environmental data at the sensor before transmission: Advances in learning and recognition will enable fast response to build up reaction strategies and decisions in real time. Decision-makers will therefore have access to sophisticated simulation models to support time-sensitive decision-making.
  - **Predictive analytics:** Understanding, generating, inferring and forecasting future environmental states from Big Data will be fundamental for digital transitions. Huge amounts of data collected through new networks of sensors (Sensors are Everywhere), and the re-use of past research data are of great support for analytical systems to discover new knowledge from the collected data. These will be sensor-based predictive models that will outperform the traditional state-of-the-art predictive methods especially in uncertain environments.
  - **Artificial Intelligence**: One key application of AI is machine learning applied to Big Data, which requires considerable computational power for training and executing the models. Applications will grow in scope and sophistication as data become more widely available and more members of the maritime community become familiar with machine learning technology and tools.

4. Persistent monitoring and digitalization of seas and oceans: The Ocean Digital Twin

Seas, oceans, and coastal areas are stressed by multiple factors (pollution, heavy maritime traffic, overfishing etc.) uniquely caused by human action (and inaction) whose severity, if not adequately managed, will deplete the marine ecosystems and destroy the biodiversity, with serious environmental, economic, and social damage. In this context, new Blue Economy strategies are pushing for further investments to allow a more effective exploitation of marine resources.

One key question is: Should we proceed in planning and developing a sustainable use of the Oceans, or should we abandon this idea, since the development of an adequate sustainability policy is too slow in producing effects when compared to the rapidity (and ubiquity) of the exploitation of marine resources?

These conflicting views on development strategies encapsulate, in essence, the dilemma in which all industrial countries find themselves nowadays. The correct, sustainable exploitation of marine resources calls for an integrated management of maritime activities that must be carefully planned, monitored, and adapted through the development of advanced integrated models capable of considering many different systems and their mutual interactions, e.g. the performance and the effects of different economic marine activities together with ecosystem and conservational models.

What we foresee here, is the rapid development of a new digital tool (Ocean Digital Twin, ODT), environment-centred, to help in analysing and preventing human-caused crises, i.e. a digital tool for climate change adaptation and protection of biodiversity and ecosystems.

The availability of Findable, Accessible, Interoperable, and Re-usable (FAIR) Big Data, the development of innovative sensors and sensor networks, and the continuous enhancement of digital technologies will be the key elements of the new approach based on the ODT concept.

Oceans are not digital, but digital is the way we have been looking at them recently and in the near future. The ODT will introduce a dynamic new paradigm for marine research, which will integrate and facilitate the combined use of existing models, technologies, and tools with new key enabling technologies, including predictive analytics, artificial intelligence, internet of things, cloud and everywhere computing, high-performance computing, virtual and mixed reality, all operating within an Open Science context.

The ODT will follow marine environmental changes over time and assess the ecosystem health, while predicting its evolution in the short and long term. It will also allow the suggestion of sustainable economic activities and the simultaneous development of biodiversity conservation strategies, through an intelligent Decision Support System able to generate different scenarios and to guide policymakers in their decisions. A virtual environment will be used to communicate and disseminate the results and to increase the involvement and the sense of responsibility of coastal communities.

New collected data will be integrated with existing data sets (the enormous amount of heterogeneous data, so called “data lake”): the ODT will assimilate past and new data through physics-based and/or data-driven models, allowing the intelligent reuse of past heterogeneous data and models via AI, cloud-based analyses, and digital data distribution.

5. Developing the Ocean Digital Twin (ODT)

The ocean, as an integrated system, can be analysed in principle by identifying the different systems of which it is composed, and their mutual interactions and hierarchies: circulation and currents, waves, tides, interaction with the atmosphere, the seabed and the sediments, coasts and estuaries, animal and plant life, the ecosystem as a whole. Some of these systems are universal, others specific to a basin, some of their mutual relations are well established and clear, others are still far from being considered consolidated.

Nevertheless, all these systems, in principle, can be dynamically "simulated" ; some using solvers based on first principles (e.g. geofluid dynamics and its equations can be used to analyse and simulate ocean circulation, currents, waves and their interaction with the atmosphere, the relative heat and momentum exchange, the transport of pollutants or sediments, etc.), others by means of data-driven models, i.e. formed by learning networks or state-space models that learn to read the data relating to a certain system (using for example, biochemical-physical sensor networks and remote sensing, and different data: oceanographic, taxonomic, bio-acoustic, bio-optical, genomic, etc.) and return a "closed box" model that learns from the data and that is able, after a training period, to return a predictive response.

Once the simulators have been developed and their mutual interactions understood and modelled, the ensemble will constitute a sort of virtual (digital) twin of the physical environment. By continuing to collect data from sensors, the ODT will follow the environment's real dynamic evolution with increasing accuracy: the ODT will evolve after the environment's life, and can be used to predict scenarios, provide intelligent management tools for planning rapid responses to unexpected and potentially harmful or catastrophic events. Examples of modelled features are the study and analysis of the evolution of marine ecosystems and their interaction with human activities, the integrated management of the coastal zone, the analysis of sedimentary processes, the examination of areas with high anthropogenic impact, the development and testing of Rapid Environmental Assessment techniques.

For the development and implementation of the ODT, it is necessary to combine different disciplinary sectors, from marine sciences to applied mathematics and Big Data analytics, digital technology and sensor development, and marine ecosystems knowledge representation. The establishment of a complex and articulated virtual environment will also become a fundamental research supporting tool, allowing data to be available with related classification, cataloguing and query environments, accompanied by new tools and analysis environments based on artificial intelligence, visualization methods in virtual and augmented reality, new integrated and intelligent management approaches for planning and carrying out missions, measurement campaigns, and collection.

6. Scalability of the model

Today it is impossible to model the full problem addressed by the ODT, i.e. the Digital Twin of Oceans or large sea basins. Major development hindrances are the lack of validated models (especially ecosystem models), the lack of data, a scarcity of sensors, computational platforms, and robustness of computational models. Fortunately, the ODT has implicit characteristics of modularity, scalability, and adaptability. At an initial stage, ODTs will be able to manage a spatially limited area (spatial scale limit), or a limited number of systems (scale of complexity limit). In this context, the possible number of interactions between systems can be varied (scale of integration) as well as the sensor network data and data typology (sensitivity scale), naturally with attention to the Big Data minimal requirements for the analysis.

These four scales, or dimensions, of the ODT can be varied starting from an initial level, relatively easy to design, build and validate, and then expanded to larger scales, enriching the ODT in complexity, depth, and utility. This will allow the model to be applied in the operational reality of marine zone management, while initially operating in parallel to more traditional management models. The ODT will support the traditional models and will learn from them, before it can be operational. At a mature stage, it will progressively explore its capabilities in practical applications.

7. Digital and human dimensions

The ODT will provide an intelligent digital environment able to overcome the limitations of the existing tools, and methodologies to integrate and process a huge number of different types of descriptors (ecological, physical, socio-economical, etc.) and to guide decision-makers in managing and planning the sustainable use of the marine resources, while offering tailor-made solutions for different areas.

The ODT virtual environment can be used to share data for research and development purposes and to provide services, as well as to communicate and disseminate the results of the analyses to stakeholders and citizens. Integral to the development of this paradigmatic system is the availability of FAIR data that come with standardized descriptions and access protocols. At the same time, compliance with the Open Science paradigm (i.e. producing re-usable, reproducible, and repeatable Science) is crucial, as it guarantees fast cross-domain applicability and flexibility in using new types of input, while supporting the repetition and reproduction of the experiments. Guaranteeing transparency in the production of results is a key feature to make them accepted by decision makers.

The ODT will be based on a hierarchy of AI models, running both at the edges of the network and on a centralized e-Infrastructure endowed with high-throughput and high-performance computing platforms. AI models will be responsible for simplifying the information flow coming from the network within a higher and higher decision hierarchy. Models will run on smart sensors in the network to activate the information flow when a particular event occurs (e.g. a concentration of vulnerable species in a certain area) and their results will go into other models that mix heterogeneous information (e.g. maritime traffic, fishing activity, area biodiversity, commercial stocks, etc.) to estimate risk indexes related with the particular event, but also with the entire ecosystem. The employed models will be heterogeneous, ranging from pure machine-learning models - that correlate sensor information with a particular phenomenon (e.g. environmental information with species habitat) - to state-space models that predict complex system dynamics with the support of natural laws as likelihood functions (e.g. population dynamics in stock assessment). By definition, the overall ODT will be a multi-disciplinary system connecting expertise from computer science, physics, engineering, and biology. Therefore, its implementation will necessarily require the use of collaborative tools.

The ODT might be offered as a network of Web Service with interfaces that follow a recognized standard to maximize its re-use from other systems external to the network of a single site. Decision tracking might be supported via computational provenance tracking at all processing levels, to maximize the transparency of the results and the understanding of the chain that brought the system to a particular decision. Finally, collaborative research in model building might be supported via Virtual Research Environments (VREs), Web-based environments that foster collaboration between users working on the same topic. VREs will also manage data and service-access policy aspects: access, security and accounting services will monitor the availability of all data and processing resources and will prevent policy violations. Using this technology, and generally Open Science-oriented facilities, will guarantee a fast development of the ODT components and the interconnection of many AI models.

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