Mobile Hybrid Structures: Feasibility and Advantages

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ABSTRACT

Several novel configurations of mobile oceanic renewable energy systems are presented with emphasis on advantages over existing planned offshore development. This paper discloses optimized configuration, maintenance and operation, and navigation of modular mobile buoyant structures utilizing wind, hydrokinetic energy, solar heat, and electrical co-generation to produce energy-intensive commodities or environmental remediation reagents including hydrogen fuel, and anhydrous ammonia. Through integrated control based on geographic information, weather data, and path cost analysis the mobile structures eliminate, mitigate, or circumvent existing risks and costs associated with resource intermittency, storage feedstock scarcity, regulatory delays, aesthetic objections, and land-use restrictions. Consideration of certain historic weather and levelized cost of energy data indicates profitable operation for various configurations presented.

Keywords: unmanned marine vehicles (UMV's), supervisory control and data acquisition (SCADA), geographical information system (GIS), velocity performance prediction (VPP), path-cost/yield analysis.

1 BACKGROUND

To date, many fixed structures for recovery of especially wind resources have been deployed offshore. Oceanic renewable energy recovery systems including wind turbines, tidal and wave energy converters and even novel high altitude airborne wind turbines all share a common feature: connection, either direct or through a substation, to the electric grid. To optimally exploit oceanic energy, which may be obtained anywhere over approximately three quarters of the surface of the planet and thus availing vast industrial growth potential, the foremost hindrance to full-scale implementation of oceanic systems is the cost of delivery from such an expansive source of energy. Proposing mobile hybrid structures herein challenges the assumption of direct grid connection through traditional offshore transmission means, thereby justifying inquiry into supplanting traditional offshore transmission with storage, on account of: installation, maintenance and operation (M&O) costs; the logistical superiority of distributed generation; round-trip energy storage/retrieval efficiency; and grid baseload capacity enhancement through efficient storage and dispatchability.

2 OVERCOMING LIMITATIONS

The proposed concept is a modular, distributed energy recovery system in which numerous mobile structures can harvest wind, hydrokinetic, and/or solar energy offshore, while being directed toward high energy wind and sea conditions, or away from overcast conditions exacerbating intermittency. The proposed system provides fundamental advantages such as eliminating expensive undersea cables and structures permanently fixed on the seafloor, expediting deployment, facilitating maintenance, simplifying permitting and regulatory compliance, and improving survivability [1]. Since the vast majority of human population is concentrated in coastal areas, this results in energy produced near the point of use, eliminating the need for new infrastructure in the form of high power transmission lines or special docking facilities, as conventional port facilities suffice. Furthermore, since no structures are permanently left offshore, the permitting process should not present the aesthetic objections and ensuing political obstacles associated with static offshore installation planning. The author herein effectively proposes innovative floating structures possessing hitherto unimplemented hybrid co-generation schemes to reduce the high Cost of Energy (COE) incurred with existing offshore systems thereby improving prospects of a most-favorable Energy Return on Investment (EROI) outcome for the final deployment.

Obvious inherent advantages of the proposed offshore renewable energy recovery system comprising one or a fleet of remote-controlled mobile hybrid structures include mitigating or circumventing prevailing new renewable resources grid or fuel infrastructure risks/costs:

- Oversubscribed grid, Curtailment losses (by storing the resource);
- Resource Intermittency (by utilizing weather and vessel path analysis);
- Storage feedstock scarcity (seawater for electrolysis or ammonia synthesis);
- Regulatory Delays (deployed in international waters under limited jurisdiction);
- Land-Use Restrictions (deployed in international waters under limited jurisdiction);
- Load Balancing and Baseload Functionality (through high-efficiency storage, delivery, dispatch);

- Installation and Maintenance Difficulty/Costs (port side manufacturing, service, distribution infrastructure already established);
- Susceptibility to Damage from Severe Weather; (rugged vessels prosper, others dock)
- Aesthetic Objections, "NIMBY“; (mobile, therefore availing deepwater, too)
- SCADA patent invigorates floating turbine concept; (stored energy over time is cubically proportional to wind/water turbine motive fluid velocity, optimized by weather prediction)
- Substantially reduces COE (M&O) by enhancing total recoverability (continuous, concurrent production, storage and delivery);
- Substantially reduces COE (M&O) with assembly line (not field) maintenance procedures.

By utilizing Geographical Information System (GIS) wind, insolation, and sea condition prediction and weather tracking technologies; and exploiting combined wind, solar, and/or hydrokinetic resources in a concurrent energy extraction and delivery process, a hybrid mobile structure innately avails rapid deployment into optimal locations, continuously adapting to maximal oceanic resources. A remote-controlled mobile vehicle also diminishes the environmental impact compared to typical fixed offshore structures while attaining a favorable EROI earlier by sustaining a high capacity factor throughout operation.

2.1 Other Mobile Ocean Renewable Systems

The Fraunhofer Center for Manufacturing Innovation and Boston University [1] has presented a mobile wave energy harvesting system. Fraunhofer proposes a hydrokinetic modular mobile system to reap the aforementioned benefits of lower cost due to no underwater cables, easier permitting, dispatchability because of storage, survivability by docking during a storm, and the logistic benefits of a distributed energy system at a cost of $0.15/kWh. The Fraunhofer proposal overlooks the potential for a hybrid approach, for instance solar photovoltaic or thermal concentration that could optimally utilize of the substantial surface area on the deck of the vessel. This paper will subsequently elucidate the benefits of the hybrid approach particularly in enhancing energy storage efficiency.

Statistical evidence indicates the validity of distributed hybrid mobile structures mitigating intermittency. For instance, a solar energy demonstration vessel, the Tûranor PlanetSolar [2], a 95 ton vessel supporting 96kW of solar panels driven by 20kW of engine power can attain a cruising speed of 7 knots, or 168 nautical miles per 24 hour period. Other researchers [3] have shown weather prediction numerical models very accurate over one to four days and that intermittency is uncorrelated over a one hour period of time when solar plants are physically separated by 150 km. Jacobson et al. [3] also noted that dispersed solar system sites also reduce variability. Geographic diversity renders the sub-hourly intermittency negligible relative to the more deterministic variability due to the changing position of the sun in the sky. Studies further report advantages of distributed wind, describing interconnection over regions as small as a few hundred kilometers apart can eliminate hours of zero net power for the system in its entirety. Similarly, Jacobson et al. [3] report the combined energy from co-located wind and wave farms reduces variability of wind and wave power individually, further corroborating the advantage of the hybrid approach proposed herein. With the above evidence, vessel velocity performance prediction (VPP) models will likely validate the obvious feasibility of re-siting mobile structures, especially with models for combined hybrid wind, hydrokinetic, and /or solar energy extraction vessels.

2.2 Unmanned Marine Vehicles

Neither Fraunhofer [1] nor PlanetSolar [2] consider unmanned operation as an EROI enhancement as proposed herein. Unmanned Marine Vehicles (UMVs) were first developed in 1993 [4]. Further evolution of UMVs as network nodes in naval applications is likely. Most often, a crew ashore or on other vessels remotely controls UMVs. This achieves the important goal of removing the human from harms way but it does not necessarily optimize the use of personnel. All wind and hydrokinetic systems have the fundamental limitation of total possible recoverable energy at any given time being directly proportional to the cube of the velocity of the motive fluids. Extant Geographic Information Systems (GIS) readily avail wind, insolation, and sea condition probability/weather tracking data from satellites as subsequently described herein. Operational cost reductions include remote controlled operation but existing technology has not fully developed the potential of intentional unmanned operation of mobile structures navigating into an environment of such high energy as to otherwise present conditions hazardous to human crews. Therefore, the author herein proposes developing remote controls operating and navigating autonomous mobile structures that can cost-effectively extract energy in an optimal manner from an environment that otherwise would present untenable risk to an on-board human crew. Existing UMV crews often execute missions in a supervisory control approach with usually the vessel low-level control (e.g. rudder actuation) computerized while the overall behavior (e.g. waypoint selection) managed by an operator [4]. This approach allows, theoretically, for one operator to oversee many UMVs, thus providing a significant economy of scale effect.

2.3 SCADA, GIS, CFD, VPP

The technology herein proposed also includes a Supervisory Control and Data Acquisition (SCADA) system [5] wherein an algorithm optimizes fuel or commodity production, storage, and delivery efficiency of modular hybrid mobile structures by accounting for wind, insolation, sea condition probability/weather tracking data from satellites, various GIS's, and from sensors on the mobile structure including GPS, Inertial Measurement Units (IMU's), fuel gauges, etc. The SCADA server side application inputs these data points to vessel Computational Fluid Dynamics and Velocity Performance Prediction (CFD/VPP) models to determine greatest yield and/or least cost path for any one of the hybrid mobile structures.

Human-machine interfaces (HMI) access a database that guides configuration of the modular hybrid structures based on commodity prices and future prices at various geographic locations and currency exchange rates; component and Line Replaceable Unit (LRU) bill-of-material (BOM) costs, reliability data, maintenance costs and schedules, material safety data sheets (MSDS); and thus a database that definitively determines and enables at an operator's discretion, action based on decisions of a universal Levelized Cost of Energy (LCOE) and commodities;

While containing data elements listed above from which to make configuration determinations, critical functionality also includes a GIS comprising not only Geospatial but also dynamic temporal data including wind speeds, insolation data, sea conditions, and weather tracking and prediction to avail data from which to base M&O and navigation decisions. Once an operator determines the best configuration for the mobile structure, its corresponding CFD/VPP model resides on the SCADA server with which a path-dependent cost or yield analysis module applies the dynamic data to the CFD/VPP model to ultimately inform M&O and navigation decisions.

Thus the implementation of the proposed SCADA involves developing an on-line cluster of integrated server-side applications, and client side user interfaces to access them. The complete system integrates several unique data structures separately comprising:

1) Weather prediction and tracking data aggregation - Geospatial Information System (GIS) development, Data from a number of satellites and map servers on one server, open source Geoserver, Geographic Resource Assessment System Software, [6] etc.

2) Commodity price and currency exchange rate database development for Levelized Cost of Energy (LCOE) Assessment;

3) System configuration database development comprising patented mobile structures and other hardware specifications, datasheets, bill-of-material (BOM) costs, material safety data sheets (MSDS);

4) Unmanned Marine Vehicle (UMV) control with the ultimate goal of high-level autonomy. The UMV control development will require an emulation platform of a Programmable Logic Controller (PLC) to simulate the vessel navigation, propulsion, and operation local control systems.

5) Vessel Velocity Performance Prediction (VPP): from a knowledge base of those who have designed sailboats and propelled vessels, adapt VPP's to enable the user to predict energy recovery by vessels specified in the configuration database (3).

6) Path cost or path yield analysis algorithm development. For instance, U.S. National Renewable Energy Lab's (NREL's) "Homer" [7] adapted especially for automated analysis of hybrid mobile ocean energy systems. The top-level integration of this data in parts (1) through (5) endows operators with the mathematical rigor to make prudent decisions on configuration, M&O, and navigation.

2.4 The Turbofoil® and Solar Cogeneration

Innovation embodied in the Turbofoil® [8] exists in the integration of a turbine coupled to a generator all within a hydrofoil reducing drag and providing lift. In delivery mode, the hydrofoil provides lift and reduces drag to a sailing vessel with its turbine gate along the foremost edge of the hydrofoil closed. When capturing energy, the turbine gate opens to allow seawater to pass through the turbine thereby generating DC herein proposed for hydrogen electrolysis or anhydrous ammonia synthesis as the storage medium for a fuel or an environmental remediation reagent.

The patent pending Solar Cogeneration Vessel (SCV) comprises concentrating solar thermal power systems (CSP) or concentrating photovoltaic power (CPV) systems on the deck of this class of mobile structure. The invention elucidates heat management techniques for both CSP and CPV systems that enhance efficiency in both systems, improves durability of CPV, and substantially enhances efficiency of energy storage by performing hydrogen electrolysis [9], [10] or ammonia synthesis [11], [12], [13] on high temperature water used to manage the heat in the CSP or CPV system.

Thus, three oceanic regimes delineated by latitudinal boundaries dictate possible configurations. In boundaries within five degrees of the equator where insolation is greatest and hurricanes rare, an SCV would prove most cost effective. Between five and twenty degrees from the equator, particularly in the Western Pacific Basin, a Turbofoil® of sufficiently rugged design to withstand structural stress from 45kt wind and fully developed seas of tropical storms would perform most profitably. Because total power is cubically proportional to motive fluid velocity in a turbine, and water is ~775 times denser than air, a Turbofoil® here will capture 27 times more power compared to typical wind turbines of similar scale in 15kt winds, availing a substantially smaller form-factor and therefore lower materials cost for equivalent energy yields. In latitudes greater than thirty degrees, a Turbofoil®

equipped vessel configured with a parasail [14] to exploit consistent high altitude winds of substantial force but lower turbulence in stable conditions yield a high capacity factor.

3 EXISTING OFFSHORE WIND COST

Installation of grid-tied delivery systems alone average cable costs $530 per kW, [15] approximately 30% of the total. Cable installation issues have resulted in significant losses, most exceeding $1M [16] with most projects experiencing some serious problems with their cable installation. Bankruptcy for cable installers is not at all unusual. For shallow and transitional depths less than 30m, the total system typically costs $1,200-$2,000 per kW [17], with moderately deep water increasingly more expensive, copper prices trending higher over time, and technology for deep water, far from shore yet undeveloped.

4 COST COMPARISON

The lowest capacity factor (15.5%) regime herein proposed, a Turbofoil® equipped vessel in the Western Pacific Basin, costing $6.5M financed at a 10% annual rate 10 year term, can achieve a 24% operating margin delivering electricity at $0.12/kWh or hydrogen at $3.19/kg while overcoming all previously stated limitations.

5 CONCLUSION

Mobile hybrid ocean energy recovery structures have been presented. Novel configurations are proven to reduce costs compared to existing ocean energy recovery systems as well as reduce or eliminate limitations impeding full-scale exploitation of oceanic energy.

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