Integration of Distributed Energy Resources into Offshore and Subsea Grids

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Abstract—**The main goal of this paper is to outline characteristics and critical aspects related to the design and operation of offshore and subsea electric distribution grids, particularly in the case of high penetration of distributed and intermittent renewable energy sources. At first, the paper provides an overview of electric loads operating in the ocean environment, surveys their power and energy demands and presents their main operational characteristics and corresponding maturity of technology. Subsequently, the potential of marine renewable energy sources is identified by analyzing their degree of development, typical power range and suitability to supply the offshore loads. Based on an up-to-date review of previous studies and real test cases, this paper shows how conditions to enable the development of "offshore smart grids" can be met and it outlines emerging trends in the electrification of the ocean space.**

Index Terms—**Deep-sea mining, marine energy, offshore grids, offshore wind, oil and gas platforms, subsea applications.**

I. INTRODUCTION

DIFFERENT types of renewable energy sources, mostly intermittent in nature, are present in the marine environment, spread over vast regions. Since oceans also host several load centers, characterized by power consumptions of dozens of MW and often located in remote areas, matching power demand and local generation through offshore electric grids could bring advantages in terms of efficiency, grid stability, sustainability and costs, compared to present supply solutions. This, however, requires the proper integration and coordination of various distributed energy systems.

The "*energization*" of the ocean space will occur, at first, through the deployment of independent offshore/subsea microgrids. The variable nature of both offshore loads and marine resources can generate bi-directional power flows, representing challenges for control and protection coordination that are non-dissimilar to those of onshore smart grids. Moreover, the prevailing operation as isolated electric systems will require the careful assessment of stability limits and power quality issues, whereas the possibility of a subsequent interconnection to other offshore systems or integration into the onshore power system, will require the elaboration of control strategies supporting the grid-connected mode of operation. The first necessary step towards the development of any offshore smart grids is, however, to gain an accurate understanding of the power and/or energy characteristics of resources and loads.

Although "moving offshore" has been clearly identified as one of the emerging challenges within the implementation of the smart grid paradigm [1], tailored analyses highlighting the criticalities of offshore grid deployments, compared to corresponding onshore applications, are scarce. In particular, available literature and previous state-of-the-art reviews tend to focus only separately on the different components of offshore and subsea distributed energy systems. Several contributions have surveyed offshore wind developments [2], [3] including floating solutions [4] or generation from other marine energy sources [5]-[7]. Other references have focused on specific offshore loads, mostly highlighting structural and construction aspects [8], [9] or surveyed offshore energy storage applications [10]-[12]. However, cross-cutting contributions are still very limited [13] and a systematic study relating the offshore power generation capabilities with the electrical loads requirements and energy storage potential in the perspective of distributed energy systems is currently missing. The goal of this paper is to contribute to filling this gap, by showing how different offshore components can complement each other and contribute to grid services provision and efficient system operation. The analysis is based on previous techno-scientific contributions, but includes also some of the newest emerging offshore technologies, such as deep-sea mining, which, due to pits novelty, has found limited space in previous papers [14].

II. ELECTRIC LOADS IN THE OFFSHORE AND SUBSEA ENVIRONMENT

Electric loads in the ocean environment (e.g. Fig. 1) are similar to concentrated industrial onshore loads. However, the space limitation, cost of maintenance and usually distance to the utility grid differentiate them from the onshore counterparts. The offshore loads can be classified based on power consumption, distance from shore, operational requirements, load cycles, and depth of operation. A significant set of representative ocean loads have been surveyed, which are classified into four main types and presented in this section based on their main application domain. Some of their characteristics are captured in Fig. 2 and Fig. 3.

A. Oil and Gas Platforms

The majority of offshore loads are represented by power consumptions associated to the Oil and Gas (O&G) industry (Fig. 1).

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Fig. 1. Snorre B O&G platform in the Norwegian North Sea (photo: courtesy of Statoil).

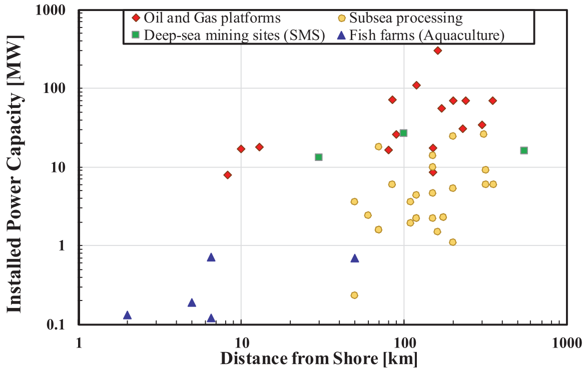

Fig. 2. Installed power capacity and distance from shore of surveyed ocean loads [15]-[61].

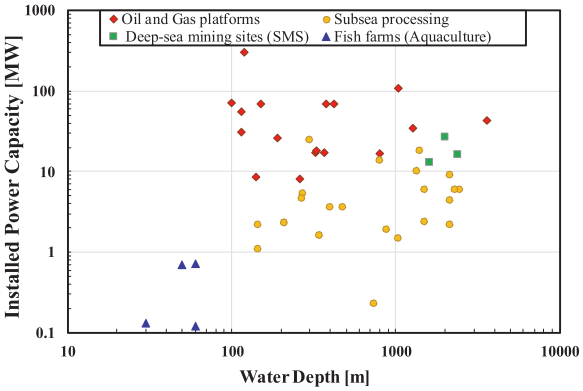

Fig. 3. Installed power capacity and water depth of operation of surveyed ocean loads [15]-[61].

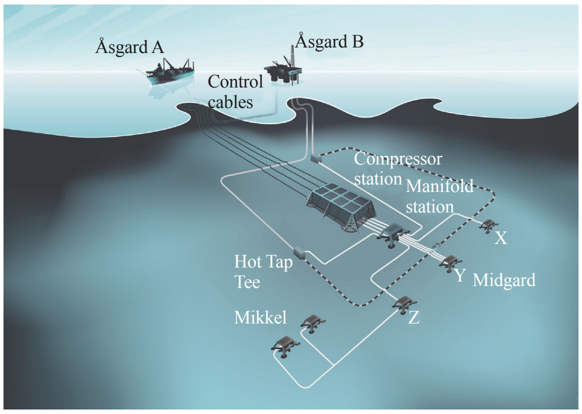

Fig. 4. Asgård gas compression station located in the Norwegian Sea at 300 m water depth with 24.4 MW power consumption (image: courtesy of Statoil).

Globally, more than 1300 O&G rigs are located offshore [62], the largest share of which are in the North Sea (185) and Gulf of Mexico (175). Although drilling an offshore well is similar to the onshore drilling process, offshore rigs face additional challenges due to the water depth (up to 3 km, and increasing, for ultradeep water applications) and the need for an anchored, stable, surface structure to host the drilling equipment and additional facilities. Moreover, compared to onshore wells, offshore O&G platforms need special equipment for oil processing and transportation after extraction. Although this significantly increases the costs (+1500%), the daily production of offshore O&G can be one order of magnitude higher than that of onshore wells and last typically for 10-20 years [63]. Typical power consumptions of offshore O&G platforms are in the range 5-300 MW [64], mostly supplied by local gas turbines [65] or diesel generators [66], [67]. Such power generation strategies cause significant greenhouse gas emissions, triggering increasing interest for more sustainable solutions. The electric distribution system of O&G platforms is characterized as a weak electric grid: power quality issues, such as high reactive power demand/low power factor [68], voltage and current harmonics, voltage notches and common mode voltages [69] may increase the losses and compromise the lifetime and operating conditions of electric components. The estimated financial loss for incidents due to poor power quality in the O&G sector is 250,000-750,000 euros per day [68]. In order to increase the energy efficiency and reduce the CO_2 and NO_x emissions, several platforms have been recently electrified, using either High-Voltage Alternating Current (HVAC) [70], [71] or High-Voltage Direct Current (HVDC) [72], depending on their power demand and distance from shore [73]. Among the advantages of “power-from-shore” solutions, in addition to high efficiency, there are high availability (~ 99%) and systems lifetime (~ 30 years), as well as reduced maintenance needs and repair time [74].

B. Subsea Processing Plants

With recent discoveries in remote and ultradeep waters and harsh environments, such as the Arctic Ocean, an additional trend in the O&G industry is to remove as many components and processing systems as possible from the floating production units and install them on the seabed (e.g. Fig. 4), reducing the required space on the platform or even removing the platform [74], [75]. Subsea processes include gas compression, boosting, water injection and separation. The main power consumptions and deployment characteristics of most of the subsea processing plants currently in operation are presented in TABLE I. Additional details can be found in [76]. Due to the extreme operating conditions, multi-MW power demands, step-out distances up to

TABLE I
Characteristics of the Main Operational Subsea Processing Plants as of February 2017 (adapted from [76])

	Name of the field or project	Basin/Country	Subsea power [kW]	Water depth [m]	Distance from shore [km]	Tie-back distance [km]
Gas compression	*Asgård, Midgård and Mikel fields (Fig. 4)*	Offshore Norway	24,400	300	200	40
Water injection	*Troll C pilot*	Offshore Norway	1,600	340	70	3.5
	Tordis	Offshore Norway	2,300	210	175	11
	Tyrihans	Offshore Norway	5,400	270	200	31
	Albacora- l'este field	Campos basin (BR)	3,600	400	110	9
Separation	*Troll C pilot*	Offshore Norway	1,600	340	70	3.5
	Tordis	Offshore Norway	2,300	210	175	11
	Parque Das Conchas	Campos basin (BR)	4,400	2,150	120	25
	Perdido	USA (Gulf of Mexico)	6,000	2,438	354	0
	Pazflor	Angola	13,800	800	150	4
	Marlim	Campos basin (BR)	1,900	878	110	3.8
Boosting	*Mutineer*	NW Shelf Australia	2,200	145	150	7
	Brenda&Nicol fields	UK North Sea	1,100	145	200	8.5
	Vincent	NW Shelf Australia	3,600	475	50	3
	Golfinho Field	Espirito Santo Basin (BR)	2,400	1,500	60	11
	Parque Das Conchas (ph1)	Campos basin (BR)	2,200	2,150	120	9
	Parque Das Conchas (ph2)	Campos basin (BR)	2,200	2,150	120	9
	Jubarte field	Espirito Santo Basin (BR)	18,000	1,400	70	8
	Barracuda	Campos basin (BR)	1,500	1,040	160	10.5
	Montanazo & Lubina	Mediterranean	230	740	50	12.3
	Jack & St Malo	USA (Gulf of Mexico)	9,000	2,134	320	13
	Rosa/Girasol	Angola	10,000	1,350	150	18
	Draugen	Offshore Norway	4,600	268	150	4
	Julia	USA (Gulf of Mexico)	6,000	2,287	320	27.2
	Parque das baleias	Espirito Santo Basin (BR)	6,000	1,500	85	10

tens of km, and operating water depths up to 3 km, the technology for subsea processing is continuously evolving. The entire power distribution system, either AC or DC, including umbilicals, protections, monitoring and control systems [77], [78], needs to be optimized: pressure tolerance, [79] and reliability [80] of the power electronics are the most critical concerns due to the prohibitive environmental conditions.

C. Deep-sea Mining

Apart from O&G applications, the boundaries of subsea operations and processing are now being pushed forward by the emerging of deep-sea mining [14], e.g. the extraction of seafloor massive sulfides (SMS) such as zinc, copper, silver and gold, in water depths between 1 and 4 km, at sites where the mineral concentration is much higher than in onshore mines. The first SMS deep-sea mining project, Solwara I, is supposed to start operation in 2018 offshore Papua New Guinea [58]. The mining of the selected site at 1600 mbsl will require heavy work-class Remotely-Operated Vehicles (ROVs). They will need to face the unprecedented technical challenges of excavation in hyperbaric conditions and ore transportation to the sea surface. Despite the similarity in the principle of operation, deep-sea mining may have higher power requirements than similar onshore mining applications. In particular, three different ROVs (Bulk and Auxiliary Miners and Collecting Machine), each with an installed power between 1.8 and 2.5 MW, are supposed to operate in this first project, in addition to the suction pump (>6 MW). The power generation capability of the supporting vessel is 31 MW for a nominal production rate of 1.8 million tons/year (dry equivalent) [58]. Since power consumptions and design considerations are strongly dependent on the depth of operation, subsea mining in deeper waters can be even more demanding [81], [82]. Moreover, a general trend in the ROV industry is to migrate from hybrid electric/hydraulic solutions to all-electric ones [83], since the use of hydraulics for power transmission can reduce the efficiency up to 50% [84], whereas the advantages of all-electric ROVs are: higher reliability, reduced size and weight, high efficiency and no leakage risks. Due to the absolute novelty and lack of any operational experience on any deep-sea mining projects, powering solutions based on renewable energies have not yet been considered, unlike the case of onshore mines, where sustainable power generation has been proposed [85], [86].

D. Aquaculture Applications

Although much less energy consuming compared to the previous applications, the aquaculture sector is one of the competitors for the use of the marine space and contributors to the offshore electric demand. In the aquaculture industry, there is a trend towards using more exposed coastal areas [87] and offshore locations [88] for fish farming, with the advantage of reducing key environmental effects, but with a possible increase in the local energy need.

The typical power consumption of fish farms is characterized by high variability, depending on the production cycles (e.g. hatchery/nursery, grow-out, harvesting or delivery phases), with the feeding phase accounting for up to 60% of the total energy consumption [89]. The maximum electric load is typically in the range 100-200 kW per installation, depending on size and location. Installed power can exceed three times the actual power demand, when locally supplied; whereas grid-connected solutions are now being implemented to mitigate the environmental impact of diesel generation [89].

III. Marine Renewable Energy Resources

Marine energy resources include both offshore wind and ocean renewable energy, where the latter category groups all possible green resources that stem from ocean waters, i.e. tidal energy, wave energy, ocean thermal energy conversion (OTEC) and salinity gradient. Offshore winds are steadier and more powerful than onshore ones, and their exploitation can minimize drawbacks such as scarcity of available land space and visual impact. On the other hand, the higher criticality and cost of Operation and Maintenance (O&M) in offshore wind farms (Fig. 5), typically reduces their availability to between 90% and 95%, whereas it is about 97% for onshore power plants [90]. Offshore wind turbines are following the technological trend of onshore wind, with a consistent increase in the average size and capacity of the installed wind turbines, which, in Europe, reached 5.9 MW in 2017 (+23% increase compared to the previous year) [91]. Some of the biggest challenges of offshore wind deployments compared to onshore ones lie in structural aspects, considered that wind turbine foundations represent a quarter to a third of the overall cost of an offshore turbine, for which installed strength, fatigue load, resistance to dynamic loadings, resistance to scour and corrosion are critical aspects [92]. From an electrical and control standpoint, power electronics covers 100% of the turbine installations since 2005 [93], and full scale power converters are increasing their share, especially for large turbines, although partially rated ones, used with doubly fed-induction generators, still dominate the market [94]. The largest offshore wind turbine is rated 9.5 MW [95] and, globally, the offshore wind capacity operational in 2017 exceeded 18.8 GW [96].

Feasibility and high performance of floating wind turbines, recently tested in array configuration [97], will further impulse the sector. Therefore, the offshore wind installed capacity is expected to reach 66 GW by 2030 [98].

Apart from wind, a significant amount of energy is present in ocean waters (Fig. 6). According to [99], the theoretical potential of tidal power (including tidal range and tidal currents) is 26,280 TWh/year; the corresponding potential of wave energy is 32,000 TWh/year and the theoretical potential associated to OTEC, (i.e. exploiting temperature differences above 20 degrees between surface and deep waters through thermal cycles), has been calculated in 44,000 TWh/year. Finally, salinity gradient (i.e. electricity production by osmotic processes exploiting the different concentration of salt in fresh and salt waters), could provide additional 1,650 TWh/year.

Fig. 5. Dudgeon offshore wind farm with 402 MW generation capacity located in the North Sea, England (photo: courtesy of Statoil).

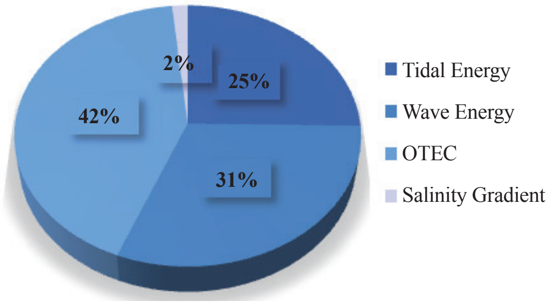

Fig. 6. Potential of ocean energy resources.

Despite the huge potential of ocean energy, the actual exploitable resource depends on the corresponding technological maturity, which is still low. Ocean thermal and salinity gradient technologies have so far been deployed only in few demonstration projects worldwide and are far from technological maturity. On the contrary, tidal energy is technologically established. Tidal barrage plants are in operation in grid connected mode both in Europe (La Rance, France, 240 MW) and Asia (Sihwa Barrage, Korea, 254 MW) [99] and tidal current harvesting has been successfully proved in several test sites [100], [101], exploiting the synergies with the wind turbines technology [99]. Wave energy was extensively researched in the last decades, but the high concept diversification [102] and need for tailored design and control solutions [103] have slowed-down the sector development, which is still at pre-commercial stage [104]. In total, in 2016, 0.5 GW of commercial ocean energy generation capacity was in operation and 1.7 GW under construction [105], 99% of which were tidal range. The estimated installed capacity of ocean energy by 2050 is up to 300 GW from wave and tidal, plus 300 GW from OTEC [102].

Other innovative renewable energy solutions have also been recently proposed to complement and diversify the offshore renewable energy portfolio. One example is constituted by floating photovoltaic plants such as those recently deployed offshore the Netherlands [106].

IV. Offshore Energy Storage

In the last years, the deployment of offshore energy storage systems (ESS) gained momentum, representing a key enabling technology for the implementation of distributed marine energy systems, in particular to mitigate the intermittency and non-dispatchability of offshore renewables. Despite the potential advantages related to the deployment close to power generation sources (i.e. reduced costs for power transmission), limited environmental and visual impact and availability of vast spaces, offshore ESS presents additional challenges compared to onshore solutions. These are due to the harsh sea environment (with risk of corrosion, chemical deterioration etc.), need of high power and energy density, low-maintenance requirements, ballasting and mooring. Still, battery solutions have been often investigated for marine applications and were recently implemented in hybrid offshore wind farms. Currently, offshore battery deployment is considered a feasible solution [107] and, from the industrial standpoint, it is seen as an extension of battery use in the maritime applications [108]. The use of fuel cells is also being considered, due to high power density and good efficiency, modularity, good dynamic load-following characteristics, and reduced emissions [109].

Apart from chemical storage, using flywheels can be a viable option [110], due to their higher lifetime, allowing a number of charge/discharge cycles in the order of 25,000-50,000. Moreover, underwater compressed air energy storage (CAES), exploiting the advantage of high hydrostatic pressure on the seabed, has been recently investigated and tested at small scale by Hydrostor [111]. Similar properties are exploited by the Underwater Pumped Hydro Storage (UPHS), as in the concepts proposed and tested by Fraunhofer institute [112], MIT [113], and other institutions worldwide [114]. Although different energy storage technologies can be considered [11] depending on the power and energy requirements of the services to be provided (as further investigated in Section V), the largest installations such as underwater CAES and UPHS face additional challenges compared to the corresponding onshore versions. These relate to the potential unavailability of vessels suitable for the deployment of large devices at water depth of hundreds of meters [115].

V. Distributed Energy Resources (DERs) to Supply Ocean Loads

The characterization of offshore/subsea electric grids as distributed energy systems was explored only recently to: 1) verify the complementarity of different offshore energy sources; 2) investigate potential, challenges and optimum sizing of ESS for ocean applications; 3) prove the suitability of offshore renewables to supply local loads, without compromising stability and efficiency of the electric grids.

In particular, [116] explores the complementarity of wind and wave energy at three different European test-sites and shows a good matching between the power production of such marine renewables and the corresponding UK electricity consumption pattern. Ref. [117] presents a similar analysis for an Irish test case. A general review of possibilities for combined wind/wave installations is contained in [118].

ESS effect on the short-term stabilization of single offshore renewable sources has been analyzed and applied, in the case of wind installations, over time intervals of 15-60 minutes (i.e. for power smoothing, frequency regulation, capacity firming etc.) in [119] and [120], as well as on longer timescales (i.e. for energy management). Studies on ESS for wave energy applications over different time horizons also exist [121]-[123]. In some cases, the analysis is extended to multiple energy resources for both short-term (power smoothing over few seconds [124]) and long-term ([125]) applications. It is worth noting that the selected domain of application for the optimal energy storage sizing is quite often that of small islands [122], [126], whose power consumption and power system challenges are, however, similar to those of isolated O&G platforms.

Whereas previous investigations on marine renewable sources and energy storage deployments targeted general offshore loads, analyses related to the use of marine renewables to meet the power consumption of specific offshore applications and the impact on the corresponding local power systems have been only recently presented. Most of the contributions target wind integration into the electric distribution systems of O&G platforms. In particular, [127] checks grid code compliance in terms of frequency and voltage stability under load start-up and loss-of-load conditions. Ref [128] considers similar scenarios, in addition to the loss-of-generation case, analyzing the integration of a large wind farm in an O&G field and performs loss analysis. In [129], voltage and frequency stability are assessed for multiple test cases, and NO_x and CO_2 emissions reduction due to wind connection is quantified. The effect of short term wind variability, however, was only taken into account in [130] and [131]: [130] is a basic energy analysis, whereas [131] includes voltage and frequency stability studies under rapidly varying wind conditions, with the goal of assessing grid code compliance, according to the IEC-61892 standard.

Finally, possible stability risks due to electro-mechanical oscillations are addressed in [132] and load management is proposed as a mitigation measure.

The use of wind power to supply subsea equipment, i.e. water injection systems, was proposed by DNV GL and found technically and economically feasible by the joint industrial project WinWin [133]. Moreover, various techno-economic studies to quantify the advantages of supplying aquaculture installations with renewable energy exist. In particular, [134] and [135] evaluate the potential of multiple energy sources (wind, ocean, micro-hydro, solar, etc.) to cover the power need of realistic fish-farms. Plans for a pilot-project using wave power to supply fish farms were proposed by Albatern in [136], whereas the use of a small-scale OTEC system for seaweed production was tested in [137]. TABLE II surveys the main aspects of subsea/offshore DER systems and related grid services investigated in recent studies.

VI. Emerging Trends in Offshore and Subsea Grids

The development of offshore and subsea electric grids, with high degree of flexibility and interconnection can be expected

TABLE II

Survey of the Main Studies Investigating Aspects of Subsea/Offshore DER Systems and Related Grid Services

	Major offshore loads					Marine renewable generation					Offshore storage			
Considered services	Generic loads	Oil and Gas platform	Subsea processing	Deep-sea mining	Aquaculture	Wind energy	Wave energy	Tidal energy	Solar energy	OTEC	Generic ESS	Batteries	CAES/ UPHS	Flywheels
Power smoothing	[121] [123]					[107][124] [125]	[121][123] [124][125]				[121] [125]	[107]	[123]	
Variability reduction	[116]					[116][117]	[116][117]							
Loss reduction/ Efficiency improvement		[128] [131]	[74]	[81]	[89] [134] [137]	[89] [107] [128] [131] [134]	[134]		[134]	[137]		[107]		[110]
Voltage stability		[64][65] [127][128] [130]				[64][127] [128][130]								
Frequency stability		[64][65] [127][128] [130]				[64][127] [128][130]								
Power quality evaluation (flicker/harmonic etc.)		[69]	[74]					[100]						
Energy management	[122]				[134] [135] [136]	[122][126] [134][135]	[122][126] [134][135] [136]	[135]	[134] [135]		[120] [122] [126]			
Load management		[132]				[132]								
CO_2-NOx Emission reduction		[64][130] [131]	[133]			[64][130] [131][133]		[101]						

in the next years, and increased monitoring [138] and control [139] capabilities will underpin the *digital transformation* [140], [141] in the offshore sector. Among the emerging trends in the deployment of such systems, *distributed energy storage integration* is ongoing, which will help mitigating renewable energy intermittency and power quality issues in the local grids. This will extend the *pervasive use of power electronics,* used for renewable energy grid integration, electric drives for ocean loads and, potentially, power conditioning for power quality enhancement. Power electronics for ocean applications will require new solutions in terms of pressure [142] and fault tolerance [143], component miniaturization and physic of failure approach for reliability analyses [144]. Furthermore, the *interconnection* of otherwise-isolated offshore electric distribution systems to *offshore HVDC and HVAC grids* will push the innovation from component-level to system-level. Considering the increasing number of offshore HVDC deployments [145], *Medium Voltage DC grids*, already emerging in the maritime sector [146], could be extended to some offshore and subsea systems [147], [148].

VII. Conclusions

The paper offers an up-to-date review of the main offshore and subsea applications. It shows the evolution of marine renewable sources and energy storage systems, outlining how their synergy can be the enabler of the ocean space energization and the adoption of smart grid models in the marine environment.

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