Electro-mechanical WEC stabilization for onshore wave energy exploitation

Pierluca Martorana
Department of Engineering
University of Palermo
Palermo, Italy
pierluca.martorana@unipa.it

Antonella Castellano
Department of Engineering
University of Palermo
Palermo, Italy

Marco Cammalleri
Department of Engineering
University of Palermo
Palermo, Italy

Vincenzo Franzitta
Department of Engineering
University of Palermo
Palermo, Italy

***Abstract*— The energy generated from harnessing sea waves is considered as a potential solution to the energy needs of small islands. The fundamental problem with the energy produced by wave energy devices is the quality of the energy itself, as it is deeply influenced by the unpredictable conditions inherent to the wave motion. Indeed, the energy produced from a direct connection between the collector and the generator is profoundly variable in terms of voltage and frequency. This prevents its direct input into the grid, as the latter is characterized by fixed frequency and voltage. The objective of this paper is to demonstrate how it is possible to normalize such energy by an electro-mechanical stabilizer.**

Keywords—sea wave, wave energy converter, power-split device, small island

I. Introduction

The economic system of modern society is constantly in search of ever-increasing energy quotas (see Fig. 1) [1]. The global electricity production has increased from 11.9 PWh/year in 1990 to 28.5 PWh/year in 2021, representing a 140% rise over 30 years. Despite the use of significantly less energy-intensive technologies by end consumers, energy needs are constantly growing at a rate of 2.8% per year [1].

Comparing these data to the European context (see Fig. 2), it is possible to observe an almost stationary trend in the same period, with a transition from fossil fuels to Renewable Energy Sources (RES).

It is now well-established that the use of fossil fuels for electricity generation has negative effects on the climate and the environment [2]. Moreover, changes in the geopolitical landscape of certain regions imply higher costs in terms of energy supply, putting the productive system of countries whose underlying economy does not have sufficient energy resources at risk [3].

Despite the progressive introduction of RES, the global production from fossil fuels continues to increase as a consequence of the even growing energy demand of developing areas, in particular Asia and South America [1].

However, the installed capacity from RES is increasing as well [4]. Globally, the electrical energy demand transitioned from 2.4 PWh/year in 1990 to 8.2 PWh/year in 2021. Despite this, more than two-thirds of electric energy is still generated annually from fossil fuels or nuclear energy. Hence, there are ample opportunities for the introduction of more sustainable energy sources. Indeed, the installation of energy production systems from RES not only improves environmental conditions but also provides the opportunity to establish conditions for each country's energy independence, avoiding the importation of fossil fuels from other territories [5], [6].

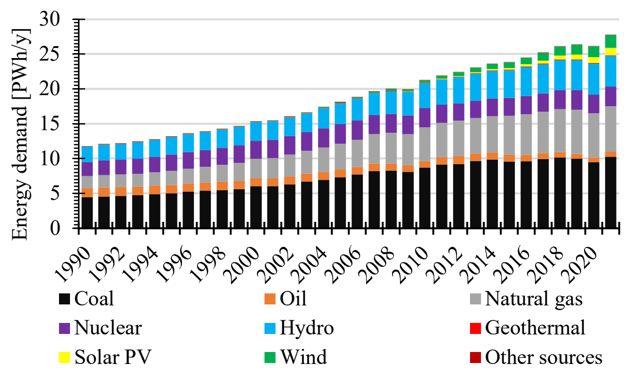

Fig. 1. Electrical energy demand in the World [1].

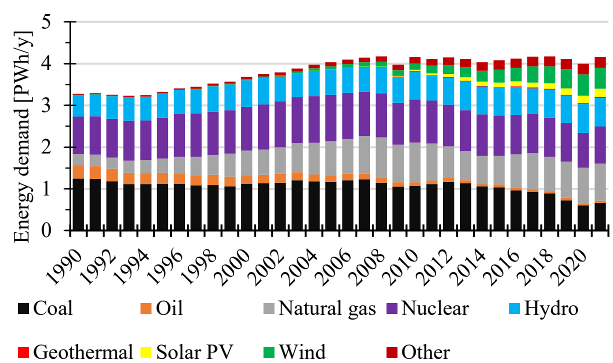

Fig. 2. Electrical energy demand in Europe [1].

In the case of Italy, in 2021, the proportion of electrical energy from RES accounts for 36.6%, which is lower than the

European average (40.0%), but higher than the world average (28.7%) [1] (Fig. 3).

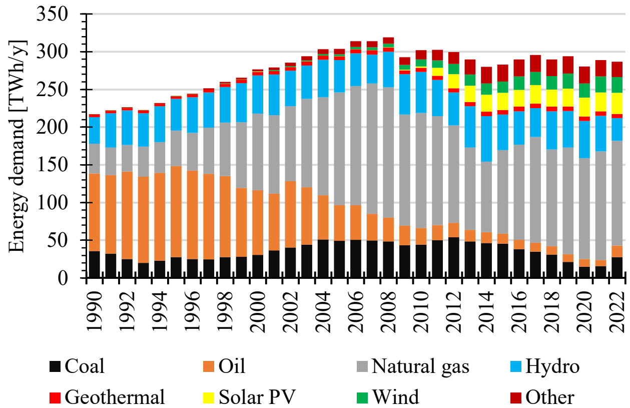

Fig. 3. Electrical energy production in Italy [1].

If at the national level the issue of renewable energy production has purely political and environmental implications, in the case of small Mediterranean islands, especially those not connected to the national electrical grid, the problems are quite different and have a much more significant impact on the daily lives of the population [7], [8]. The data from the Observatory on minor islands, within a project named "Sustainable Islands" identify a series of indicators [9]:

- I.1) Soil
- I.2) Waste management
- I.3) Water and purification
- I.4) Energy
- I.5) Sustainable mobility

The average sustainability index of the islands is 40%, indicating there is ample room for improvement in the near future, especially concerning energy supply. Currently, the islands with the lowest sustainability indices in the entire Italian island panorama are Ischia with 29%, Elba at 26%, and La Maddalena with a sustainability index of 21% [10].

In the described context, especially for islands not connected to the national electrical grid, electricity generation relies on outdated, inefficient diesel generators that are highly polluting [11]. The main issues of the energetic scenario of small islands are:

- **Inefficient energy supply**: Many islands depend on obsolete, inefficient, and polluting diesel generators for electricity production.
- **Low sustainability indices**: Islands at the bottom of the national ranking have significantly low sustainability indices, highlighting the need for substantial interventions.
- **Seasonal energy coverage issues**: To overcome the huge variation of load during the year and avoid significant changes in energy efficiency, the old systems must be composed of many engines, of which some of them are used only for a limited period of the year.
- **Need for infrastructure improvements**: Islands require investments in infrastructure to enhance key sectors such as waste management, water purification, and sustainable mobility.

The most critical aspects are the following:

- The electrical grid is relatively small and operates independently, exhibiting limited innovation.
- There is a pronounced reliance on fossil fuels, which are imported from other territories, notably the mainland.
- The adoption of RES is modest, constrained by environmental considerations aimed at preserving the landscape.
- Significant fluctuations in electrical demand seasonally occur, primarily driven by the considerable impact of tourism.

As a result, maintenance expenses are high because power plants are intentionally oversized to provide ample backup power for handling seasonal energy demand variations and potential diesel generator failures. Moreover, operating costs for electrical energy production are significant due to the small scale of plants and the need to import fuel.

In this context, considering the stringent regulations on the environmental impact regarding the installation of RES generators, a steadfast denial towards the installation of wind generators, the impossibility of creating sufficient water reservoirs for hydroelectric power plants, and the low energy density of photovoltaic systems [12], it becomes highly intriguing to examine the energy inherent in wave motion.

Harnessing sea waves can exploit offshore and nearshore areas that are currently underutilized, averting potential competition for land use as seen with other energy sources. Wave-based facilities could be seamlessly integrated into existing harbors, serving the dual purpose of pier protection and energy production. Sea waves could also create local job opportunities [13].

A multitude of wave energy technologies have been evaluated, some of which have been developed and tested in laboratories or open sea environments [14]. Given the diverse range of solutions in literature, various classifications are employed, considering aspects such as working principle, device orientation, position relative to sea level, distance from the coastline, etc. [15], [16]. A classification based on wave propagation direction introduces the following definitions [17]:

- **Attenuator**: A device parallelly oriented to the wave direction, adapting its shape to the wave profile.
- **Point Absorber**: A system characterized by axial symmetry, designed to collect wave energy regardless of the wave direction.
- **Terminator**: A device oriented perpendicularly to the wave direction where the wave breaks to harness its energy.

In terms of working principles, popular definitions include [18]:

- **Oscillating Water Column (OWC)**: Waves enter and exit a submarine chamber to pressurize and depressurize an air-filled chamber, powering a wind turbine specifically designed for this application.
- **Wave Activated Bodies (WAB)**: A system composed of floating buoys producing relative motion to run energy converters.
- **Overtopping**: A device that collects kinetic energy by filling a water reservoir with waves, then produces electrical energy by spilling water from the reservoir through a low-head hydro turbine.

Numerous examples exist in the literature, such as Kværner Brug [19], Limpet [20], Mighty Whale [21] for OWC systems; Wavebob [22], Power buoy [23], Pelamis [24], Oyster [25] for WAB systems; and Tapchan [26], Wave Dragon [27], and Slotcone [28] for overtopping systems.

Despite the array of proposed technologies, no commercial systems are currently available. In this context, at the Department of Engineering of the University of Palermo, an innovative device is under development [29]. This technology is based on an electro-mechanical motion converter capable of transforming oscillating rotation into unidirectional rotary motion to power commercial generators, similar to those used in small wind turbines [30].

One of the most challenging issues is the electrical energy production from fluctuating RES. As well known in literature [17], [31], the electrical grid requires energy inputs with a very selective requirement (expressed by the concept of Power Quality), among which the fixed frequency (50 Hz ± 0.5 Hz), voltage (230 V ± 10 V) and a limited presence of harmonics (Total Harmonic Distortion lower than 8%) [32]. In order to keep under control these parameters, it is mandatory to achieve a fixed speed for a rotary machine, like alternators.

An alternative solution is nowadays represented by the utilization of inverters to decouple the angular speed of the machine extracting energy from the RES and the electrical frequency. This approach is currently used in variable-speed wind turbines, to maximize the extraction of energy, thanks to the possibility of changing the angular speed of blades according to the wind speed, without affecting the electrical frequency of the power output [33]. However, this solution is not applicable to wave energy harvesting due to high fluctuations of this source.

In the case of wave energy, the current options are represented by [17]:

- Store wave energy, in an intermediate form of energy, and use it according to the desired power output, such as in the overtopping devices using low-head hydro turbines, or wave activated bodies equipped with high-pressure alternative pumping.
- Use an asynchronous generators coupled with air turbine. The generator initially absorbs energy from the grid to achieve the rated angular speed and to be ready to extract the impulsive energy of waves, collected by the air reserve in the OWC.

The aim of the authors is to design an electro-mechanical motion converter to convert the variable oscillating motion of waves into a regular rotary motion able to run commercial alternators. This technology could allow the coupling of a simple floater and rotary machine, avoiding the storage of energy in intermediate form and maximizing the efficiency of the entire process.

II. Wave Energy Converter

The paper introduces a wave energy converter designed for the installation in harbors to harness the energy of sea waves for the generation of electrical energy while simultaneously protecting the piers [34]. The concept is depicted in Fig. 4.

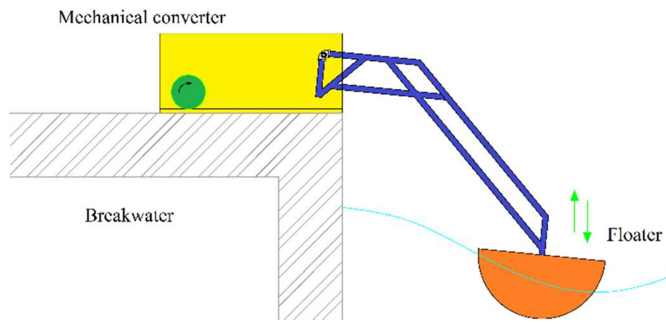

Fig. 4. The proposed wave energy converter.

A floating buoy is employed to capture the mechanical energy of waves, generating rotation around the main hinge of the device. The mechanical conversion process takes place within a transmission system, described in Section III, that can be situated on the breakwaters. On the output axis, a commercial generator can be incorporated to generate electricity.

A direct coupling between the output shaft of the collector and the generator would pose a series of operational limits. Indeed, from a kinematic point of view, the motion of the collector, generated by the driving force of sea waves, is a vertical oscillation. Assuming that the wave motion can be represented by a sum of harmonics, the problem is reduced to the study of a sinusoidal function, expressed by Eq. 1:

$$z(t) = \frac{H_s}{2}\sin\left(\frac{2\pi}{T_p}t\right) \quad (1)$$

where $z(t)$ represents the vertical position of the collector. The relation considers the significant wave height H_s and the peak period T_p.

In order to evaluate the specific of the wave energy converter, the authors considered the wave climate in the Mediterranean Sea, by using data collected by the Italian Measuring Network (in Italian RON “Rete Ondametrica Nazionale”) in the station of Mazara del Vallo (Sicily, Italy).

In Fig. 5, the authors evaluated the probability density function (PDF) of the peak periods of waves observed in Mazara del Vallo. Fig. 6 reports the PDF of the significant waves.

According to the following graphs, it is possible to observe that the most frequent wave conditions are:

$$0.3\ m \leq H_s \ \leq 1.3\ m$$

$$4\ sec \leq T_p \ \leq 6\ sec$$

Due to the simplification to assume a sinusoidal wave, the corresponding vertical speed $v_z(t)$ is given by:

$$v_z(t) = \frac{\pi H_s}{T_p} \cos\left(\frac{2\pi}{T_p} t\right) \qquad (2)$$

The speed of the floater varies from a minimum of 0.18 m/s to a maximum of 1.5 m/s.

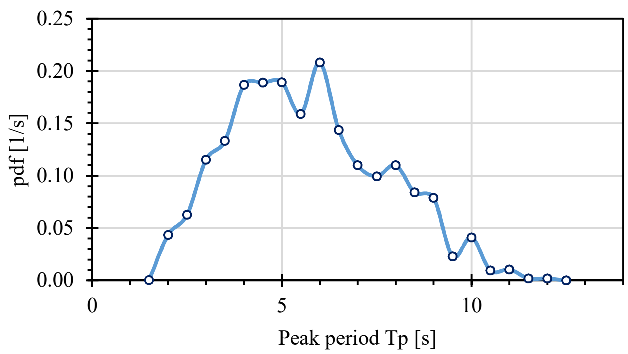

Fig. 5. Probability density function of peak period in Mazara del Vallo.

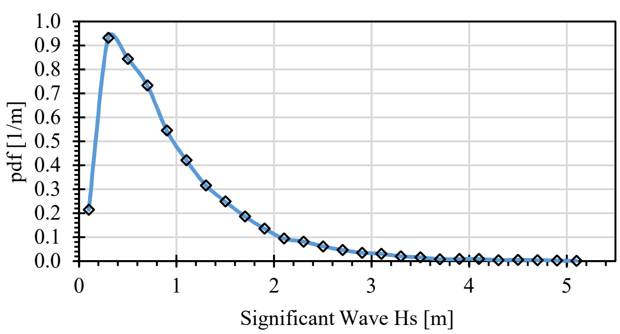

Fig. 6. Probability density function of Significant Height in Mazara del Vallo.

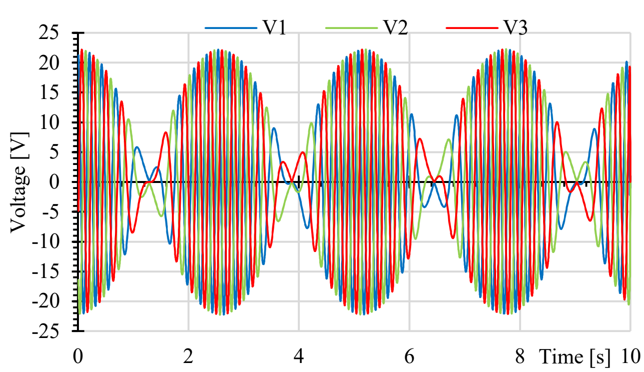

Fig. 7. Open circuit voltage trends of a three-phase generator, working at oscillating speed.

Supposing that the conversion from the buoy translational motion to the generator rotational motion is performed through a fixed speed ratio, the generator is directly coupled to the output shaft of the collection system. In this case, it is evident how the energy produced by the generator exhibits significant variability in both voltage and frequency. By way of example, Fig. 7 shows the open circuit voltages produced by a three-phase generator running at pulsating speed.

The next section introduces a mechanical conversion system to achieve a stable angular speed of the generator.

III. Mechanical System for Motion Conversion and Stabilization

As outlined in Section II, the wave motion causes an alternative vertical motion of the floating buoy at low speed that needs to be converted into the high-speed unidirectional rotational motion of the generator rotor. To this purpose, the mechanical system shown in Fig. 8 has been conceived, where the motion conversion is split into two steps: 1) conversion from an alternative translational motion to a low-speed unidirectional rotational motion, and 2) conversion from a low-speed unidirectional rotational motion to a high-speed unidirectional rotational motion.

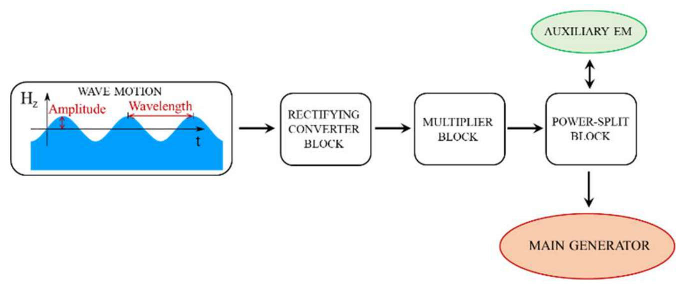

Fig. 8. Energy conversion system

The first conversion is performed by a rectifying converter block: the buoy motion in input drives a planar mechanism designed so that the output linkage has a low and unidirectional rotational speed. The second conversion occurs in the multiplier block, consisting of ordinary gear trains and chain drives designed so as to multiply the speed in input to the multiplier up to a rotational speed as close as possible to the generator desired speed.

Nevertheless, the mechanisms deployed in the rectifying converter and multiplier blocks do not allow any speed regulation. As a result, the generator speed is coupled with the buoy speed, which depends on the aleatory wave motion. To overcome this issue and decouple the generator speed from the wave motion, the power-split block is introduced.

This solution has been deployed on some hybrid electric vehicles to kinematically decouple the internal combustion engine from the wheels through the intervention of an electric unit that operates as a speed variator [35], [36], [37], [38], [39].

In the wave energy converter, the power-split block decouples the generator speed from the speed in output from the multiplier through the tuning of the speed of an auxiliary electric machine (EM). Hence, the generator operations can be realized at a stable functioning point. The auxiliary electric machine can operate as a motor or as a generator depending on the difference between the speed in output from the multiplier and the desired generator speed. When operating as a generator, the resulting electric power can be stored to be released afterwards, when the motoring operation is required.

An integrated design of the multiplier and power-split block that makes the speed in input to the power-split block as similar as possible to the generator desired speed enhances efficiency.

IV. Control Problem

The deployment of the power-split block ensures an additional kinematic degree of freedom that implies the need for the implementation of a control strategy to manage the actuators operations [40], [41]. In particular, the regulation of the main generator speed is performed through a control strategy that tunes the speed of the auxiliary EM according to the instantaneous rotational acceleration of the main generator for a given wave motion in input to the mechanical conversion system. Nonetheless, undesired inertial effects and actuation delays prevent an exact instantaneous tuning. Thus, the deployment of one or two flywheels, adequately designed, may be necessary for more precise motion stabilization.

A flywheel is a mechanical device that operates as a mechanical energy accumulator since it can store energy during acceleration phases and release it during deceleration phases. In this way, the effects of the aleatory wave motion can be significantly mitigated.

V. Conclusion

In this manuscript, the authors proposed a new solution for the wave energy harvesting. The idea is the adoption of an innovative electro-mechanical converter able to rectify and stabilize the angular speed obtained from the angular rotation of a floater around a hinge.

This technique allows a more regular electrical energy production from the main generator. This technology is inspired by the power-split speed variator, currently adopted on hybrid vehicles.

In future works, a prototype will be tested in laboratory, in order to evaluate the producibility and the energy efficiency of this solution.

Acknowledgment

The work presented is carried out thanks to the technical and operational support of Engcosys Enterprise and Emar Srl.

References

[1] IEA, "Energy Statistics Data Browser." Accessed: Feb. 10, 2024. [Online]. Available: https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=ITALY&fuel=Energy%20supply&indicator=TESbySource

[2] M. Meinshausen *et al.*, "Greenhouse-gas emission targets for limiting global warming to 2 °C," *Nature*, vol. 458, no. 7242, pp. 1158–1162, Apr. 2009, doi: 10.1038/nature08017.

[3] Y. Agarwala, "100 % Renewable Energy Transition In Small Island Developing States (SIDS). A Quick Scan Backcast for 2 islands in the Caribbean – Curacao and Grenada," Delft University of Technology.

[4] IRENA, "Statistical Profiles." Accessed: Jul. 27, 2023. [Online]. Available: https://www.irena.org/Data/Energy-Profiles

[5] R. Ferroukhi *et al.*, "Renewable Energy and Jobs," no. December, pp. 1–144, 2013, doi: 10.1158/1078-0432.CCR-16-2586.

[6] T. Bulavskaya and F. Reynès, "Job creation and economic impact of renewable energy in the Netherlands," *Renew Energy*, vol. 119, pp. 528–538, 2018, doi: 10.1016/j.renene.2017.09.039.

[7] D. Curto, S. Favuzza, V. Franzitta, R. Musca, M. A. Navarro Navia, and G. Zizzo, "Evaluation of the optimal renewable electricity mix for Lampedusa island: The adoption of a technical and economical methodology," *J Clean Prod*, vol. 263, p. 121404, Aug. 2020, doi: 10.1016/j.jclepro.2020.121404.

[8] D. Curto, V. Franzitta, A. Viola, M. Cirrincione, A. Mohammadi, and A. Kumar, "A renewable energy mix to supply small islands. A comparative study applied to Balearic Islands and Fiji," *J Clean Prod*, p. 118356, Sep. 2019, doi: 10.1016/j.jclepro.2019.118356.

[9] Battistelli F. *et al.*, "SUOLO, RIFIUTI, ACQUA, ENERGIA, MOBILITA', DEPURAZIONE. Le sfide della transizione ecologica nelle isole minori," 2023. [Online]. Available: www.isolesostenibili.it

[10] Lega Ambiente, "Isole Sostenibili: osservatorio sulle isole minori," 2020.

[11] D. Milone, D. Curto, V. Franzitta, A. Guercio, M. Cirrincione, and A. Mohammadi, "An Economic Approach to Size of a Renewable Energy Mix in Small Islands," *Energies (Basel)*, vol. 15, no. 6, p. 2005, Mar. 2022, doi: 10.3390/en15062005.

[12] A. Parisi, R. Pernice, A. Andò, A. C. Cino, V. Franzitta, and A. C. Busacca, "Electro-optical characterization of ruthenium-based dye sensitized solar cells: A study of light soaking, ageing and temperature effects," *Optik - International Journal for Light and Electron Optics*, vol. 135, pp. 227–237, Apr. 2017, doi: 10.1016/j.ijleo.2017.01.100.

[13] V. Di Dio, V. Franzitta, F. Muzio, G. Scaccianoce, and M. Trapanese, "The use of sea waves for generation of electrical energy and Hydrogen," in *OCEANS 2009*, IEEE, Oct. 2009, pp. 1–4. doi: 10.23919/OCEANS.2009.5422319.

[14] V. Franzitta, D. Milone, M. Trapanese, A. Viola, V. Di Dio, and S. Pitruzzella, "Energy and Economic Comparison of Different Conditioning System among Traditional and Eco-Sustainable Building," *Applied Mechanics and Materials*, vol. 394, pp. 289–295, Sep. 2013, doi: 10.4028/www.scientific.net/AMM.394.289.

[15] D. Curto, V. Franzitta, A. Guercio, and M. Trapanese, "Testing a linear ironless generator for the sea wave energy harvesting," *Oceans Conference Record (IEEE)*, p. 5, 2022, doi: 10.1109/OCEANSChennai45887.2022.9775494.

[16] D. Curto, V. Franzitta, A. Guercio, E. R. Sanseverino, A. Vasile, and G. Zizzo, "Assessing optimal energy mix and stability in the island of Favignana," in *13th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2022)*, Institution of Engineering and Technology, 2022, pp. 425–429. doi: 10.1049/icp.2023.0030.

[17] D. Curto, V. Franzitta, and A. Guercio, "Sea Wave Energy. A Review of the Current Technologies and Perspectives," *Energies (Basel)*, vol. 14, no. 20, p. 6604, Oct. 2021, doi: 10.3390/en14206604.

[18] V. Franzitta, A. Viola, and M. Trapanese, "Design of a transverse flux machine for power generation from seawaves," *J Appl Phys*, vol. 115, no. 17, p. 17E712, May 2014, doi: 10.1063/1.4865883.

[19] WavePowerLab, "Kværner Brug's OWC device." Accessed: Aug. 30, 2021. [Online]. Available: http://wavepowerlab.weebly.com/what-is-that-wec/kvaerner-brugs-owc-device

[20] T. J. T. Whittaker, W. Beattie, M. Folley, C. Boake, A. Wright, and M. Osterried, "The Limpet Wave Power Project – The First Years Of Operation," *Renewable Energy* - *Whittaker*, pp. 1–8, 2004.

[21] OES-Environmental, "Mighty Whale." Accessed: Oct. 06, 2021. [Online]. Available: https://tethys.pnnl.gov/project-sites/mighty-whale

[22] J. Weber, F. Mouwen, a. Parish, and D. Robertson, "Wavebob – Research & Development Network and Tools in the Context of Systems Engineering," *Ewtec*, no. Proc. of the 8th European Wave and Tidal Energy Conf., Uppsala, Sweden, pp. 416–420, 2009.

[23] Ocean Power Technologies, "PB3 POWERBUOY." Accessed: Oct. 06, 2021. [Online]. Available: https://oceanpowertechnologies.com/pb3-powerbuoy/

[24] E. Rusu and C. Guedes Soares, "Coastal impact induced by a Pelamis wave farm operating in the Portuguese nearshore," *Renew Energy*, vol. 58, pp. 34–49, Oct. 2013, doi: 10.1016/j.renene.2013.03.001.

[25] P. Evans, "Oyster ocean power system to provide 1 GW by 2020," New Atlasfile:///C:/Users/andre/Documents/UNIPA/Dottorato/Art. Santi Romano/review/articoli in introduzione/1-s2.0-S0306261920313702-main.pdf. [Online]. Available: https://newatlas.com/oyster-ocean-power-system/11180/

[26] Ecthelion, "Norwave Wave Power Plant," sketchfab. [Online]. Available: https://sketchfab.com/3d-models/norwave-wave-power-plant-482851fc4c8041d99d456289c01dc764

[27] P. Bak, J. Peter, Peter Frigaard; Jens Peter Kofoed1 & Wilfried Knapp2, 1Dept. Civil Engineering; Aalborg University;, and T. U. of Munich, "Wave Dragon: wave power plant using low-head turbines," in *Hidroenergia 04: International Conference and Exhibition on Small Hydropower General*, Falkenberg, 2004.

[28] M. Buccino, D. Banfi, D. Vicinanza, M. Calabrese, G. Del Giudice, and A. Carravetta, "Non breaking wave forces at the front face of Seawave Slotcone Generators," *Energies (Basel)*, vol. 5, no. 11, pp. 4779–4803, 2012, doi: 10.3390/en5114779.

[29] D. Curto *et al.*, "An Experimental Comparison between an Ironless and a Traditional Permanent Magnet Linear Generator for Wave Energy Conversion," *Energies (Basel)*, vol. 15, no. 7, p. 2387, Mar. 2022, doi: 10.3390/en15072387.

[30] D. Curto, V. Franzitta, A. Guercio, and G. Napoli, "First analyses on a mechanical motion converter to produce electrical energy from sea wave," in *Global Oceans 2020: Singapore – U.S. Gulf Coast*, IEEE, Oct. 2020, pp. 1–7. doi: 10.1109/IEEECONF38699.2020.9389068.

[31] D. Curto, V. Franzitta, A. Guercio, R. Musca, A. Vasile, and G. Zizzo, "Stability Analysis in a Vietnam Small Island for the Deployment of a Nearshore Wave Power Plant," *2022 Workshop on Blockchain for Renewables Integration, BLORIN 2022*, pp. 236–241, 2022, doi: 10.1109/BLORIN54731.2022.10028639.

[32] CENELEC, *CEI EN 50160. Voltage characteristics of electricity supplied by public distribution networks*. 2010.

[33] D. Curto, A. Guercio, M. A. Judge, and F. Montana, "A Review on Wind Power Simulation Models," in *2023 Asia Meeting on Environment and Electrical Engineering (EEE-AM)*, IEEE, Nov. 2023, pp. 01–06. doi: 10.1109/EEE-AM58328.2023.10395176.

[34] D. Curto *et al.*, "Introduction of Offshore Wave, Wind and Solar Energies in Vietnam," *2020 Global Oceans 2020: Singapore - U.S. Gulf Coast*, 2020, doi: 10.1109/IEEECONF38699.2020.9389219.

[35] L. Wang, Y. Cui, F. Zhang, and G. Li, "Architectures of planetary hybrid powertrain system: Review, classification and comparison," *Energies*, vol. 13, no. 2. MDPI AG, 2020. doi: 10.3390/en13020329.

[36] B. M. Conlon *et al.*, "The Next Generation 'voltec' Extended Range EV Propulsion System," *SAE International Journal of Alternative Powertrains*, vol. 4, no. 2, pp. 248–259, 2015, doi: 10.4271/2015-01-1152.

[37] M. Cammalleri and A. Castellano, "Analysis of hybrid vehicle transmissions with any number of modes and planetary gearing : kinematics, power flows, mechanical power losses," *Mech Mach Theory*, vol. 162, p. 104350, 2021, doi: 10.1016/j.mechmachtheory.2021.104350.

[38] A. Castellano and M. Cammalleri, "Power Losses Minimization for Optimal Operating Maps in Power-Split HEVs: A Case Study on the Chevrolet Volt," *Applied Sciences*, vol. 11, no. 17, p. 7779, Aug. 2021, doi: 10.3390/app11177779.

[39] A. Castellano, P. Stano, U. Montanaro, M. Cammalleri, and A. Sorniotti, "Model predictive control for multimode power-split hybrid electric vehicles: Parametric internal model with integrated mode switch and variable meshing losses," *Mech Mach Theory*, vol. 192, Feb. 2024, doi: 10.1016/j.mechmachtheory.2023.105543.

[40] M. Cammalleri and D. Rotella, "Functional design of power-split CVTs: An uncoupled hierarchical optimized model," *Mech Mach Theory*, vol. 116, pp. 294–309, Oct. 2017, doi: 10.1016/j.mechmachtheory.2017.06.003.

[41] A. Castellano, D. Leone, and M. Cammalleri, "Design of a Hybrid Electric Power-Split Transmission for Braking Energy Recovery in a Drilling Rig," *Designs (Basel)*, vol. 6, no. 5, Oct. 2022, doi: 10.3390/designs6050074.