OFFSHORE SOLAR IN HIGH SEAS – ASSESSMENT OF RESOURCE COMPLEMENTARITY FOR A CASE IN MALTA

J. Meit*, J. C. S. Amato*, B. Vlaswinkel*

**[1]Oceans of Energy, Wassenaarseweg 75, Valkenburg, The Netherlands*
**brigitte.vlaswinkel@oceansofenergy.blue*

Keywords: OFFSHORE SOLAR, HYBRID OFFSHORE ENERGY PROJECTS, MEDITERRANEAN SEA, HIGH WAVES, RESOURCE ASSESSMENT, CABLE POOLING.

Abstract

This paper reports on the potential of offshore solar to enhance offshore wind energy projects. Offshore solar is a novel technology for which first systems by Oceans of Energy have surpassed high wave environmental conditions for over 3,5 years and have received Approval in Principle certification. The system can be installed at offshore wind sites where it offers benefits in terms of spatial use, meteorological resource complementarity, and environmental synergies. New resource assessments have been conducted to test the complementarity of wind and solar patterns at a site offshore the island of Malta to assess benefits in the EU-Mediterranean region. The addition of +100% offshore solar in a wind farm configuration resulted in +41.3% additional power output and thereby a potential decrease of -29.2% in offshore infrastructure costs. The gains are especially realized during Spring and Summer periods which tend to be more energy intensive in the region, and are therefore considered of high value for balancing the energy system. The merits demonstrated provide a strong case for further assessing the potential of offshore solar integrated within wind farms, which could possibly act as a gamechanger in driving the (regional) offshore wind industry to accelerate implementation of projects.

1 Introduction

1.1. Need for Offshore Solar

Offshore solar is a novel technology and a rapidly developing industry. Given that 70% of the Earth's surface is covered by water and 50% of the world's population live within 100 km distance from shore [1], offshore solar energy can significantly contribute to the global push towards renewable energy sources. Offshore solar technology provides an additional alternative to installing photovoltaic (PV) power plants on land, which is especially of importance for areas where land resources are limited [2,3] or unsuitable for PV installations due to urbanization, nature or agricultural use [4]. The offshore solar technology consists of floating platforms with integrated conventional PV-modules that form arrays, are kept stationary offshore by a mooring and anchoring system, and supply power to the end-user with a power export system. The offshore solar farm system design needs to account for the harsh environments at sea, that include the *1 in 100 year* storms with corresponding winds and waves and the salty corrosive environments, and is therefore different compared to other floating solar applications [5].

Technology capable of withstanding this environment has been in 2023-Q2 for 3.5 years operational in high wave conditions on a MW-scale in the Dutch North Sea by the Oceans of Energy offshore solar farms, and has been tested in a few other smaller pilots incl. at Malta [6]. Next projects are planned, incl. at the offshore wind farm "Hollandse Kust Noord" developed by Crosswind (Shell/Eneco consortium) [7] and at the "Hollandse Kust West" windfarm developed by RWE, which are both located in The Netherlands. It is envisioned that offshore solar farms will be increasingly more common, which is being taken up by Governments across Europe incl. The Netherlands which has targeted 3 GW by 2030, Belgium, and Malta. As a very densely populated country with scarce land resources, the combination of offshore wind and solar could make a huge contribution to the future climate-neutral plans of regions such as Malta [8].

1.2. Advantages of offshore solar at windfarms

The benefits of adding offshore solar to offshore wind farms are threefold: a) First of all, the offshore solar farms (with a power density of 100-200 MW/km2 compared to 5-10 MW/km2 for offshore wind [9]) fit very well in-between the space of offshore wind turbines and therefore can be easily spatially integrated. Modern turbines of ~15 MW will allow for spacing of 1.5-2.5 km to limit losses from wake effects, enabling 1 km^2 scale areas that can be used for a solar farm; b) Secondly, earlier research [9,10,11,12] shows that meteorological solar- and wind patterns are complementary to each other, depending on the offshore location. This means that the energy production of wind (which is larger in harsh weather, in autumn/winter) and solar (which is larger in calm weather, in spring/summer) can be combined and integrated on the same electrical infrastructure. This so-called "cable-pooling" results in higher capacity factors of the energy infrastructure and the savings derived from this can offset lost revenues from curtailment (which is when, during certain

https://doi.org/10.1049/icp.2023.1550

timeframes, power output of the combined generation system exceeds the power export capacity). This may be particularly interesting for offshore projects, where the power export infrastructure costs are high, and where the benefits of a more stable power output are shown to lower transmission losses and infrastructural costs, and benefit power system stability [11,12]; c) Thirdly, in the context of sustainable marine spatial planning and the need to take into account increasingly busy sea spaces, this kind of multi-use leaves more sea space left untouched for nature, recreation, fishing or other Blue Economy activities. Particularly aquaculture activities can possibly benefit from co-location with offshore solar, as the natural wave dampening effect of the floating platforms creates a calmer sea for the farming of seaweed and hang-culture mussels. From an environmental point of view, offshore solar can offer chances for nature [13], as the floating reefs increase biodiversity and attract fish, and nature-inclusive mooring designs can result in positive impacts on the marine ecosystem.

1.3. Offshore Solar Developments

The Netherlands is taking a leading role in moving the novel technology of offshore solar towards commercial applications with world's-first demonstration pilots by Oceans of Energy (Figure 1). The Technology Readiness Level (TRL) of this design is 7, which means a prototype has been tested and demonstrated in the operational environment.

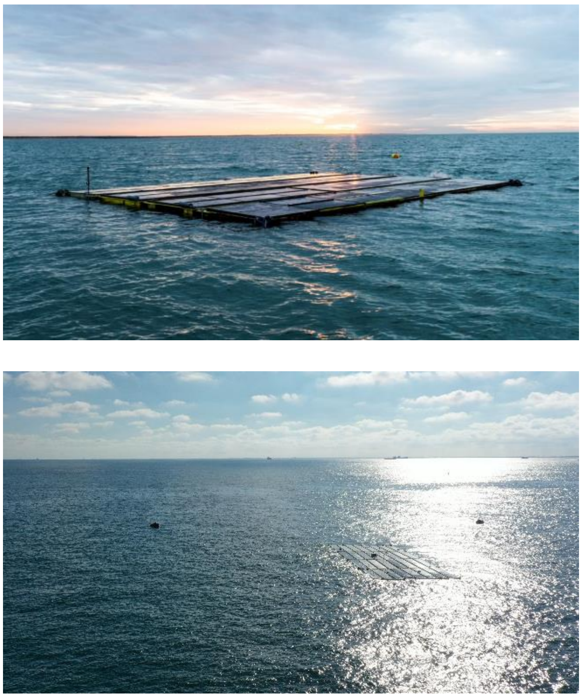

Figure 1. (**a**) First modules of the offshore floating solar array of Oceans of Energy installed nearshore in the Dutch North Sea in 2019; (**b**) Sixty-four (64) interconnected modules creating a floating farm with one-third the size of a football field, operational 12 km offshore from The Hague, the Netherlands since 2020. Farm will be expanded to 1 MW-size in 2023

The Oceans of Energy technology is based on a modular and scalable concept, which resembles the dynamic and flexible behaviour of a floating mattress to minimize environmental loads and to increase material efficiency, and is build up from rigid and interconnectable pontoons that are capable of withstanding the exposure to the offshore environment. The technology has recently been rewarded with the Approval in Principle certification from Bureau Veritas and has a targeted design lifetime of 25+ years. The technology is designed as such to minimize operational needs while establishing high performance. Oceans of Energy envisions that by 2030 the installed capacity to be of 3 GW and that total market size for offshore solar by 2050 is in the 20-40% range of the total solar-PV industry.

First projects are emerging in countries with a relatively mature offshore wind industry in the North Sea, in which the benefits of the multi-use and cable-pooling result in endorsements from Governments to tendering parties for offshore wind concessions. In NL bidders at recent offshore wind tenders have therefore included offshore solar in their bids and NL Government is developing policy to enable a 3 GW installed capacity by 2030 to meet the national renewable energy targets [14]. It is expected that offshore solar can result in larger gains in markets where solar resources are better and where offshore wind is facing more challenges. An example of such a region could be the EU-Mediterranean (EU-MED), where solar resources are better compared to North Sea (150+%) and where wind resources tend to be lower (<80%). Moreover, offshore wind faces additional difficulties in EU-MED in terms of permitting, with shores that are widely used for recreation. The planned wind farms are therefore typically located further offshore and are in deeper waters, resulting in higher costs for the grid connection infrastructure and for a need to develop (more expensive) floating wind turbines (instead of fixed-bottom monopile solutions).

Combining offshore solar with the offshore wind plans in EU-MED can therefore become a possible gamechanger to implement large renewable offshore energy projects in the region, as of the additional yields and the cost savings in terms of project development and infrastructure. This conference paper studies these potential benefits from a resource perspective for a case study in Malta. The objective is to enlarge understanding of the merits and complementarity of solar and wind energy generation offshore in the EU-MED as a possible means to accelerate rollout of offshore renewables in the region.

2 Methodology

2.1 Data usage and experimental set-up

To assess the potential benefits of combined offshore solar and wind farms, we used the OOE-OSI1 Model, which is a Python-based Offshore Solar Integration model developed at Oceans of Energy that simulates a combined energy system, i.e. an offshore solar farm integrated in an offshore wind farm connected to the transmission system, and is assumed to operate in stable conditions. The meteorological data serving as input is from the MERRA 2 dataset, collected from 2017 to

2022, conveniently on an hourly time resolution and includes, among others, wind and solar irradiation data. Therefore, the power output directly translates to hourly energy production. These data were obtained from the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science Program [15], using coordinates corresponding to the EEZ Area 1 (35°90'32" N, 14°79'36" E) in Malta.

The experiments, consisting of computational simulations of a combined offshore energy system off the coast of Malta, are partitioned in two sections. Firstly, we studied systems in 4 different configurations using the above-mentioned data. The configurations are listed in table 1 (C1: Full Integration; C2: High Export; C3: High Wind; C4: High Solar). Secondly, we performed a sensitivity analysis to address the effect of solar-to-wind installed capacity ratio on various complementarity metrics, especially for when the offshore solar farm is used to exceed the power export capacity (i.e. 'overplanting').

Installed Capacities	C1	C2	C3	C4
Offshore Wind [MW]	105	105	105	60
Offshore Solar [MWp]	105	105	52.5	105
Power Export Capacity [MW]	105	135	105	105

Table 1. Overview of combined energy system configurations simulated with the OOE-OSI1 Model for a Malta offshore

2.2 Offshore Wind Farm Modelling

To model the offshore wind farm, we used the IEA 15-MW offshore reference wind turbine with a hub height of 150 m above sea level and a rotor radius of 120 m [16]. The former is considered by extrapolating the wind speed, measured at 10 m, using a logarithmic extrapolation function as encountered in the work of Costoya et al. [8]:

$$v_h = v_{ns} \frac{\ln(h) - \ln(z_0)}{\ln(h_{ns}) - \ln(z_0)} \tag{1}$$

We compute the wind speed v_h at the hub height h using the near surface wind speed v_{ns}, measured at a height of 10 m, and the surface roughness z_0 obtained from the MERRA 2 dataset. The wind speed is translated to wind turbine power output by means of a power curve, shown in figure 2.

The model uses the cubic power formula, considering varying density obtained from the MERRA 2 dataset, in between the cut-in and rated wind speed. Herein, the power coefficient encompasses aerodynamic, mechanical, and electrical losses.

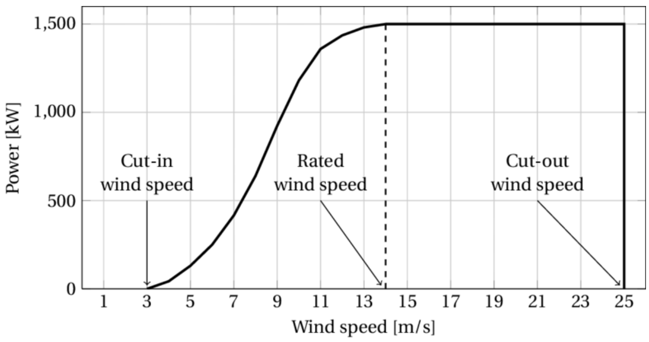

Figure 2. An example of a power curve for a 1500 kW wind turbine. Adapted from [16].

However, to compute the yield of the wind farm we must account for losses due to wake effects (from turbines 'shading' each other and taking the wind resources). We simplified the wake effect and assumed a loss of 10% for the wind farm as encountered in the earlier work of Golroodbari et al. [7].

$$P_{farm} = \frac{N}{2} A \rho C_p {v_h}^3 \eta_{wake} \tag{2}$$

Equation (2) shows the power output of a wind farm made up of N turbines with swept area A , wind speed at hub height v_h, wake efficiency η_{wake}, power coefficient C_p, and air density ρ.

2.3 Offshore Solar Farm Modelling

The computation of offshore solar farm yield consists of three steps. Firstly, we must perform computations on the solar irradiance components. We obtain the direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), and surface albedo (ALB) from the MERRA 2 dataset, and the solar zenith (ZEN) and azimuth (AZI) are simulated with functions of the *PVlib* open-source python library [18]. Subsequently, we compute the global horizontal irradiance with equation (3), where θ_z is the solar zenith:

$$ghi = dni + dni \cos(\theta_z) \tag{3}$$

Secondly, we compute the solar cell temperature due to various combined heating and cooling effects. Considering the temperature of solar cells is of paramount importance for power output computations as higher cell temperatures lead to a lower efficiency [19]. The Mattei 1 Model [20] is used to calculate cell temperature considering among others the ambient temperature, convection due to surface winds, and the modules' heat exchange capabilities. To improve the model precision, we used the Heat Index (HI) value described by

Brooke Anderson et al. [21] for the ambient temperature, which accounts for the relative humidity of the ambient air.

An offshore solar specific computation is that of PV module cooling by sea water for which we use the methodology proposed by S.Z. Golroodbari and W. Sark [19]. Herein, the volumes of the PV floater and the surrounding sea water are assumed to be finite and equal. Furthermore, assuming the PV floater and the sea water are at the same temperature, the cell temperature T_c and the PV floater temperature T_f reach thermal equilibrium T_{eq} according to equation (4). The latter is used as the operating temperature of the PV module to compute its power output using the Sandia PV array performance model from the *PVLib* library [18].

$$m_p c_p\left(T_c - T_{eq}\right) = m_f c_f\left(T_f - T_{eq}\right) \tag{4}$$

In conclusion, to account for electrical losses in inverters, we use the *NREL PVWatts V5* model. The inverter has a nominal efficiency of 96% and varies as a function of load fraction compared to its nominal power [22].

2.4 Combined Farm and Complementarity Metrics

To study the combined offshore farm in a "cable pooling" setting, we modelled a power export constraint shown. That is, when the power output of the combined farm exceeds the power export capabilities of a so-called substation, the energy sources are curtailed and the power transmitted is equal to the export capability. In this study, we propose a scheme in which solar power is curtailed first. Only in the case where solar power output is zero, wind farm power can be curtailed.

In the present work we define a combination of size dependent and size independent complementarity metrics to quantify the effect of co-locating offshore solar and wind farms. In Table 2 we list less conventional metrics to quantify complementarity in a co-located offshore energy farm.

Variable	Name	Unit
PS	Power Smoothing Index	%
LOLP	Loss of Load Probability	%
NLP_{12h}	12 h No Load Periods	*N*
C_r	Curtailment Factor	%

Table 2. Overview of non-conventional resource complementarity metrics used to assess offshore energy system performance

The Power Smoothing Index is adapted from the work of M. Lopez et al. [9] and quantifies the smoothing of the power output due to the addition of an offshore solar farm to an offshore wind farm. More precisely, the percentual difference in coefficient of variation in a combined farm CV_{ws} compared to that of an offshore wind farm CV_w and is computed by means of equation (6).

$$PS = \frac{CV_w - CV_{ws}}{CV_w} \tag{5}$$

Therefore, a decrease in coefficient of variation, i.e. a smoother power output over time, results in a positive value. The *LOLP* originates from the field of power system reliability [21], where it quantifies the probability that a power system cannot supply the demanded load due to failures. In this context, we compute the number of hours as a ratio of total hours in which the system does not supply any load due to unfavourable meteorological conditions. The *LOLP* is closely related to the NLP_{12h}, which is the number of periods larger or equal than 12 hours in which the system does not supply any load. Especially, we observe the differences between the *LOLP* and NLP_{12h} between a combined farm and an offshore wind farm. Lastly, we study the curtailment of energy sources, which is the potentially generated energy that couldn't be supplied as of the constraints in the power export capacity.

3 Results

Firstly, we discuss the effect of adding offshore solar to offshore wind on the non size-dependent metrics, namely the NLP_{12h} and the *LOLP*. On average, we observe a drastic reduction in the NLP_{12h} from 29.6 to 4.4 periods per year; likewise, the *LOLP* changes from 13.98% to 6.56%. This does, however, give an incomplete picture of the energy system performance.

In Table 3 the results are listed for all four configurations. In this context, it must be mentioned that the capacity factor of a standalone offshore wind farm (without solar) is 37.8% at the site, which is never curtailed due to no overplanting and due to the curtailment scheme proposed in this work. Furthermore, we note that at the site a standalone offshore solar farm would have a capacity factor of 18.5% when unbounded by power export constraints.

The offshore solar capacity factor is high in all four configurations compared to capacity factors in more Northern regions (9-12% for North Sea) [7] and offers a large contribution to the energy yield of the offshore energy project. Especially in C1, cable utilization is increased dramatically with a capacity factor increasing from 37.8% for a wind-only configuration to 53.4% for a combined configuration. In return, curtailment plays a more significant role lowering the capacity factor of the solar system to 15.6%. In addition, the effect of wind-to-export installed capacity ratio is observable on the difference in capacity factor between C3 and C4, where the capacity factor is highest in the latter due to the proposed curtailment scheme. In terms of energy yield, considering that the Maltese electricity demand is projected to increase up to 3000 GWh in 2027 [22], the configurations could supply between 12.1% and 17.0% of power, from which offshore solar can supply up to almost half (45.5% in C4).

Variables	C1	C2	C3	C4
System Energy Yield [GWh/y]	491.1	511.0	425.3	364.5
Energy Yield Solar [GWh/y]	143.6	163.6	77.9	166.0
Capacity Factor Solar [%]	15.6	17.8	16.9	18.1
Curtailed Energy [GWh/y]	26.4	7.8	7.1	4.0
PS Index [%]	28.3	24.6	20.3	20.6
Capacity Factor Power Export [%]	53.4	43.2	46.2	39.6

Table 3. Modelling results for four configurations of a combined offshore energy farm off the coast of Malta, quantifying energy system performance and resource complementarity, modelled at Oceans of Energy.

Figure 3 shows seasonal fluctuations in combined energy output for C1 and the smoothening effect of offshore solar. The output of offshore wind can be between 4 to 6 times lower in summer compared to the winter whilst, trivially, offshore solar output is significantly higher during summer.

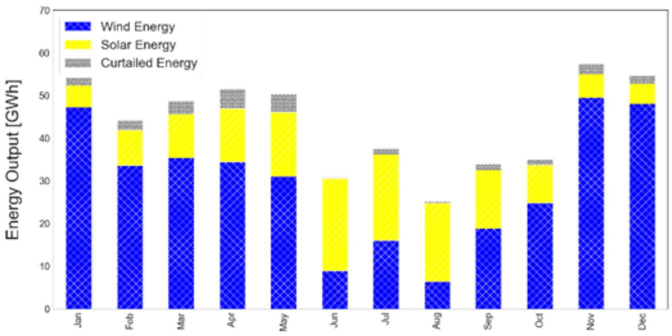

Figure 3. Monthly energy production (first month is January) and curtailment of a 105 MW wind farm, 105 MWp solar farm and 105 MW export cable in the year 2017 (configuration 1), modelled with the OOE-OSI1 Model for a location off the coast of Malta.

These opposing seasonal trends dampen one another resulting in a more stable energy yield over time. Interestingly, the fluctuations in solar energy output are not as big as those of wind energy, leading to higher curtailment in winter then in summer. Considering that the energy systems in the region are possibly more extensively used during Summer (tourist seasons, more air-conditioning, dry seasons with more desalination needed), the balancing value of utilization during summer may be of large importance.

As we have seen, system size plays a significant role in energy system performance, especially the ratio between solar and wind installed capacity ratio. Figure 4 shows the effect of solar-to-wind installed capacity ratio R on various metrics. Firstly, data on the additional output generated by the solar farm, fitted to a second-degree polynomial, shows that the effect of adding offshore solar capacity degrades especially after $R = 1.25$. Furthermore, curtailment is almost zero up to $R = 0.1$ and increases to almost 40% at $R = 2.0$. Lastly, the power smoothing effect increases very strongly until about $R = 0.75$ after which it dampens slowly, indicating that the added value of offshore solar increases sharply to smoothen the power profile until about 75% solar-to-wind installed capacity. Thereafter, the power smoothing effects decreases further.
.

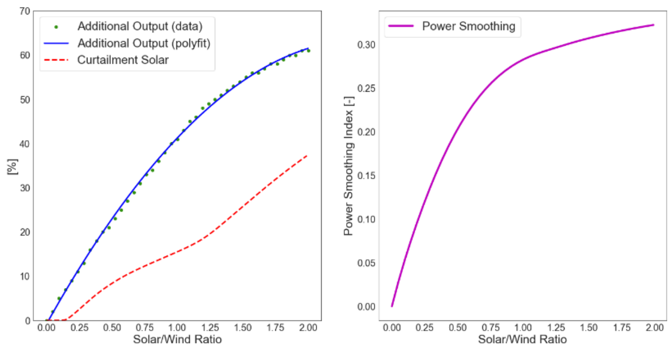

Figure 4. Sensitivity Analysis of Solar-to-Wind Installed Capacity Ratio to additional output by an offshore solar farm, solar energy curtailment, and the power smoothing index, for 105 MW installed Wind capacity and 105 MW power export capacity (C1) modelled with the OOE-OSI1 Model for a location off the coast of Malta.

4 Discussion

This research used the OOE-OSI1 Model, developed at Oceans of Energy, to assess for the first time the complementarity of offshore solar and offshore wind in the EU-Mediterranean region by means of a case study of Malta. The results suggest that the addition of offshore solar to an offshore wind farm results in a significant increase in the utilization of offshore export systems in the region and that regardless of curtailment the capacity factors of offshore solar (>15%) tend to be significantly larger in EU-MED than in North Sea Regions (<12%) where offshore solar is emerging fast. The findings suggest that the economic feasibility of such integration is beneficial in terms of 1) the sales of additional power yields from solar (+41.3% in C1 compared to standalone offshore wind) and 2) the cost savings of supplied power in terms of project development and energy infrastructure (-29.2% in C1 compared to standalone offshore wind). Further research is needed to quantify the benefits and compare them with the costs of offshore solar technology.

Moreover, this study has not assessed the equipment needed to integrate the offshore solar farms and the technical feasibility of these integration effort. However, based on experience from OOE and on first integration projects on the North Sea (Hollandse Kust Noord and Hollandse Kust West), these are not expected to become possible showstoppers. Similarly, benefits such as synergies between the technologies in the installation and operational phase have also not been included in the scope of the study.

The assessment of the four configurations demonstrates that regardless of full-overplanting of the system (C1), the additional yields of the offshore energy project are increasing and are above the levels of offshore solar systems in North Sea regions. Based on the sensitivity analyses, it is suggested that the benefits of adding offshore solar increase sharply until the point of 75% solar to wind installed capacity ratio and afterwards slower. The configuration of 100% (C1) results in more curtailment per MW installed, although this can be offset by additional benefits from scaling the systems and by larger cost sharing of the infrastructure. It is therefore recommended to develop offshore solar in these regions as an addition to wind farms in 1 : 1 configurations. Increasing the power export capacity from 105 to 135 MW (C2) results in a 4% increase in yearly supplied power. This may become attractive in case the costs of the power export system are less than the expected benefits from the additional yield.

The results furthermore indicate that the energy pattern is significantly improved in terms of a reduction in periods without power supply and especially in terms of seasonal complementarity. Regardless that each MW of offshore wind generates about 3x as much energy yearly compared to solar, the contribution of solar raises especially the utilization during periods and seasons when wind power outputs are low. This results in less dependency on the intermittence of wind and allows for benefits in terms of grid operations. Especially considering that the region's energy use may be more intensive during the summer periods in which high energy consumption from tourism, air-conditioning, and desalination may be peaking, it becomes very attractive to generate more energy during these low-wind periods from the offshore infrastructure. In near future, when energy storage and energy conversion (such as hydrogen) can become of larger importance, the energy infrastructure may be largely benefited for relying less on the wind resources. To further study this, it would be recommended to include these large scale multi use combined offshore energy farms in energy system models of the region that include consumption and possibly outlooks on storage/conversion.

Finally, this study is focused on a single location in the EU-MED and not on reality-based configurations. It would be interesting to extend the scope of this study for comparisons with other regions in the EU-MED than Malta to explore possible regional variances. Furthermore, the scale of the *100 MW range* is arbitrary and used for research purposes only. Typical offshore energy projects tend to be of much larger scale and can easily 10-20x as large. A minimum size of 500 MW is genuinely of interest for project developers. The results of this study can however be multiplied and are therefore also illustrative for such cases. As a next step, it would be recommendable for Governments and/or project developers to suggest sites with wind farm scale configurations to assess the scale on a realistic level.

5 Conclusion

The complementariness of solar- and wind resources in the EU-MED allow for beneficial energy generation combinations of integrated offshore solar at offshore wind farms. Overplanting an offshore wind project with +100% offshore solar results in annual power output increases of +41.3% and thereby reductions in infrastructure costs of -29.2% compared to wind-only. Expected curtailment of the power from offshore solar is limited and results also when included in higher capacity factors than solar PV plants in countries such as Germany, Netherlands, and Belgium.

The energy profiles of a combined system enable a more stable energy pattern, that results in less periods of low energy generation and in a better distribution of energy generation during the year. The offshore solar energy generates in particular more power during the less-windy Spring and Summer seasons, which coincide often in EU-MED with more power intensive drought- and tourist seasons. It is therefore expected that a combined offshore energy project results in additional value in both terms of generation & utilization as in value for grid stabilization & complementariness.

6 Acknowledgements

The OOE-OSI1 Model has been developed as part of the EU-SCORES project, funded by the European Commission through the Horizon-2020 Green Deal program of CINEA. The EU-SCORES project focuses on accelerating multi-use offshore energy farms consisting of offshore wind with combinations of offshore solar and/or wave energy.

7 References

[1] Vo T.T.E., Ko H., Huh J., Park N.,Overview of possibilities of solar floating photovoltaic systems in the offshore industry, 2021, Energies, 14, 21, DOI: 10.3390/en14216988

[2] A. Sahu, N. Yadav, K. Sudhakar, Floating photovoltaic power plant: A review, Renewable and Sustainable Energy Reviews, 2016, 66, 815-824, https://doi.org/10.1016/j.rser.2016.08.051.
[3] R. Bugeja, L. Mule' Stagno, N. Branche, The effect of wave response motion on the insolation on offshore photovoltaic installations, Solar Energy Advances, 2021,1, https://doi.org/10.1016/j.seja.2021.100008.
[4] J. van Zalk, P. Behrens, The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S., 2018, Energy Policy, 123, 83-91, https://doi.org/10.1016/j.enpol.2018.08.023.
[5] TNO, Challenges and potential for offshore solar. February 2022; Topsector Energie
[6]'Prototypes - SolAqua', https://offshoresolar.org/prototypes, accessed 28 April 2023
[7] 'Oceans of Energy to Build Offshore Solar Array at Hollandse Kust Noord Offshore Wind Park', https://www.offshorewind.biz/2023/04/25/oceans-of-energy-to-build-offshore-solar-array-at-hollandse-kust-noord-offshore-wind-park/, accessed 28 April 2023
[8] Malta's 20230 National Energy and Climate Plan (2019)
[9] S.Z.M. Golroodbari, D.F. Vaartjes, J.B.L. Meit, A.P. van Hoeken, M. Eberveld, H. Jonker, W.G.J.H.M. van Sark. Pooling the cable: A techno-economic feasibility study of integrating offshore floating photovoltaic solar technology within an offshore wind park. Solar Energy.Volume 219.(2021).Pages 65-74. ISSN 0038-092X.https://doi.org/10.1016/j.solener.2020.12.062
[8] X. Costoya et al. "Combining offshore wind and solar photovoltaic energy to stabilize energy supply under climate change scenarios: A case study on the western Iberian Peninsula". In: Renewable and Sustainable Energy Reviews 157 (2022), p. 112037. issn: 1364-0321. doi: https://doi. Org/10.1016/j.rser.2021.112037
[9] Mario Lopez, Noel Rodriguez and Gregorio Iglesias. "Combined Floating Offshore Wind and Solar PV". In: Journal of Marine Science and Engineering 8.8 (2020). issn: 2077-1312. doi: 10.3390 / jmse8080576. url: https : / / www.mdpi.com/2077-1312/8/8/576
[10] Soukissian T.H., Karathanasi F.E., Zaragkas D.K. "Exploiting offshore wind and solar resources in the Mediterranean using ERA5 reanalysis data" In: Energy Conversion and Management, 237 (2021). art. no. 114092. DOI: 10.1016/j.enconman.2021.114092
[11] Lauria, S., Schembari, M., Palone, F. and Maccioni, M. (2016), Very long distance connection of gigawatt-size offshore wind farms: extra high-voltage AC versus highvoltage DC cost comparison. IET Renewable Power Generation, 10: 713-720. https://doi.org/10.1049/iet-rpg.2015.0348
[12] Diab, A.A.Z., Sultan, H.M. & Kuznetsov, O.N. Optimal sizing of hybrid solar/wind/hydroelectric pumped storage energy system in Egypt based on different meta-heuristic techniques. *Environ Sci Pollut Res* **27**, 32318–32340 (2020). https://doi.org/10.1007/s11356-019-06566-0
[13] Hooper et al., (2021) Environmental impacts and benefits of marine floating solar; *Solar Energy*, 219, 11-14; https://doi.org/10.1016/j.solener.2020.10.010
[14] Rob Jetten, Minister of Energy and Climate, Rijksoverheid. Derived from: https://www.rijksoverheid.nl/actueel/nieuws/2023/04/26/extra-pakket-maatregelen-dicht-gat-tot-klimaatdoel-2030 on 1st of May 2023.
[15] 'NASA Prediction of Worldwide Energy Resources', https://power.larc.nasa.gov/#resources, accessed 20 February 2023
[16] E. Gaertner et al., 'Definition of the IEA 15-Megawatt offshore reference wind turbine' (IEA, March 2020), pp 4-5
[17] Hamon, C.: 'On Frequency Control Schemes in Power Sytems with Large amounts of Wind Power'. Licentiate Thesis, KTH Royal Institute of Technology, 2012
[18] William F. Holmgren, Clifford W. Hansen, and Mark A. Mikofski. "pvlib python: a python package for modeling solar energy systems." Journal of Open Source Software, 3(29), 884, (2018). https://doi.org/10.21105/joss.00884
[19] S. Z. M. Golroodbari and W. van Sark. "Simulation of performance differences between offshore and land-based photovoltaic systems". In: Progress in Photovoltaics 28.9 (2020), pp. 873–886. doi: https://doi.org/10.1002/pip.3276
[20] Mattei, M., Notton, G., Cristofari, C., Muselli, M., & Poggi, P. (2005). Calculation of the polycrystalline PV module temperature using a simple method of energy balance. https://doi.org/10.1016/j.renene.2005.03.010
[21] Brooke Anderson, G., Bell, M. L., & Peng, R. D. (2013). Methods to calculate the heat index as an exposure metric in environmental health research. Environmental Health Perspectives, 121(10), 1111–1119. https://doi.org/10.1289/EHP.1206273
[22] Dobos A. P.: PVWatts Version 5 Manual. https://pvwatts.nrel.gov/downloads/pvwattsv5.pdf
[23] B. W. Tuinema, J. L. R. Torres, A. I. Stefanov, et al. Probabilistic Reliability Analysis of Power Systems. Apr. 2020
[24] 'Malta - Country Commercial Guides - Energy', https://www.trade.gov/country-commercial-guides/malta-energy, accessed 3 february 2023