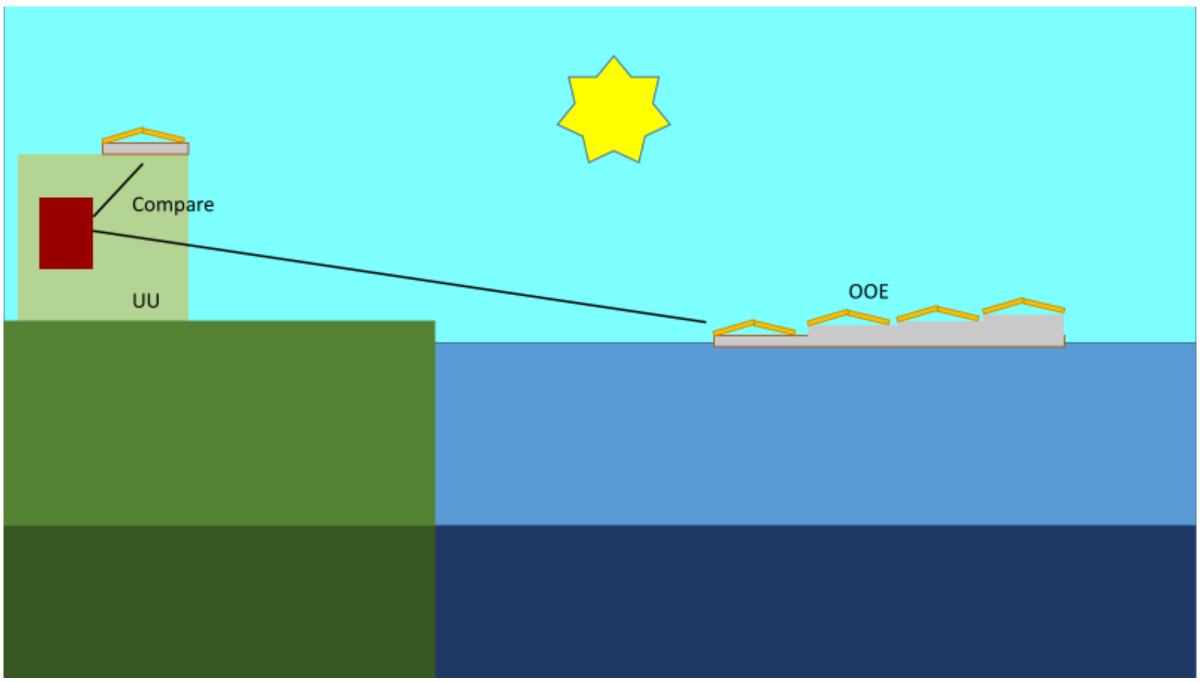
Comparative Analysis of PV at SEA versus PV on LAND

CSEALAND



Final report (public)

Oceans of Energy

Utrecht University

Public report

Project details

Projectnumber:	TEUE117066
Project title:	Comparative Analysis of PV at SEA versus PV on Land
Coordinator:	Universiteit Utrecht
Partners:	Oceans of Energy
Project period:	1 February 2018 – 31 December 2021

Contact details

This report is created by the project partners. For questions regarding the project, results and follow-up projects you can contact:

Universiteit Utrecht
Wilfried van Sark
+31 30 2537611
w.g.j.h.m.vansark@uu.nl

Subsidy

The project was supported with a subsidy from the Dutch Ministry of Economic Affairs, National EZ subsidies, Topsector Energie, performed by the Rijksdienst voor Ondernemend Nederland (RVO).

Cover

Summary

The sea is the largest unused area in the world which offers opportunities for renewables as these require otherwise space on land. Scientifically valid comparisons between PV on land and PV at sea are today still inexistent.

In this project a modular floating PV system has been developed that can be upscaled to large scale PV installations at sea. In parallel a simulation model has been developed that allows comparing performance differences between offshore floating and land-based PV systems. This model includes wave-induced motion and cooling due to sea water.

The project has resulted in the realization of a floater system that can function off-grid, and that includes measurement equipment for monitoring power generation as well as ambient conditions. An energy management system including batteries was designed.

The simulation model showed that an offshore PV system would generate about 13% more energy compared to a land-based system, which can be attributed to increased irradiance at sea in combination with cooling due to the sea water.

The validation of the model that was planned by installing the floater at sea and comparing energy yields with a land-based system was not possible. The original floater design was found to be unsuitable for stand-alone offshore deployment and thus was never installed at sea. The land-based system was designed and installed but acquired data could not be compared.

Nevertheless, the findings show that levelized cost of electricity of an offshore PV system is more favorable than anticipated.

Preface

This final report describes the work performed in the project CSEALAND (Comparative assessment of PV at SEA versus PV on LAND) as carried out within the framework of the Nationale regelingen EZ-subsidies, Topsector Energie, executed by the Rijksdienst voor Ondernemend Nederland. The report addresses the results obtained. In addition, several project changes, mostly due to the Covid pandemic, are described.

Contents

1. Introduction

Photovoltaic solar electricity (PV) is generally considered essential to a future decarbonised energy economy [1-3]. Its power generation capacity has been growing strongly throughout the world, reaching up to 900 GW at the end of 2021 [4]. Both observations also hold for the Netherlands: future climate-neutral scenarios project PV to generate up to one third of total electricity demand in 2050 [5], which due to electrification of energy demand is projected to increase two- or threefold. PV deployment in the Netherlands has been showing an average 50% annual growth rate for over a decade now and has reached 14 GW capacity at the end of 2020 [4]; growth is expected to continue in the next decades.

The renewable energy transition in the Netherlands poses enormous challenges, specifically in terms of land use for renewables, and more recently the limited availability of electricity transport capacity. This causes stakeholder conflicts, resulting in more expensive projects (higher rents, longer procedures) and less CO_2 reductions (projects remain smaller, implementation times are longer, less projects). Various studies have resulted in area requirements for PV at various area types, such as roof tops, infrastructure, terrains. Water areas have been included recently [7], and especially offshore locations for PV provide a large potential for the Netherlands, viz. about 45 GW, which is similar to roof top and agricultural potential [7]. To limit sea area usage, large floating PV installations are foreseen to be integrated within offshore wind parks, making double use of the same sea area as well as using the same export cable to land [6]. A circa 200 TWh/yr offshore PV potential, as estimated recently [8], corresponds to using 50% of the available area within offshore wind parks, if these are deployed to 60 GW, the upper ranges in the energy scenarios for 2050 [5].

There are many places around the world that do not have enough land for PV installations, such as Japan, Singapore, Korea, Philippines, island states such as Malta, the Maldives [9], and demand for FPV is growing at those locations [10]. Floating solar systems can be installed at water bodies like oceans, lakes, lagoons, reservoir, irrigation ponds, wastewater treatment plants, wineries, fish farms, dams and canals, also showing the potential for dual use of water bodies. Moreover, due to the fact that more than 50% of the entire world population lives within 100 kilometers of an oceanic coast FPV system installed at sea can be conveniently located to supply energy to these regions [11].

Floating solar exists at (reservoir) lakes and other inshore water bodies, commercially. Early research indicated that the energy yield of floating solar is generally >10% compared to installations on land

[12,13]. The floating systems at lakes cannot be used for applications at sea, due to the tempestuous wind- and wave conditions. Only a few commercial solar farms exist at protected sea sites such as fjords, within atolls or nearshore, and limited research has been done while interest is growing. In conclusion, at the start of this project, no design existed, nor any design had been actively tested or developed, that is truly suitable for offshore conditions.

In this project a modular floating module has been developed that can be upscaled to large scale PV installations at sea. Everything in and around this module is designed to resist sea conditions during 25 years at sea, to be maintained and installed efficiently and safely. Each module can be built on land, or transported over land or sea to an assembly site near the project location and towed to its permanent location. By combining more modules a larger area can be covered. It is the ambition to develop mid-scale (MWp) and large-scale (GWp) PV systems at sea in the years to come. The technological innovation will lead to several new markets: PV in-between wind turbines, PV for (congested) offshore oil & gas platforms that otherwise burn diesel or gas, PV together with offshore wind to generate hydrogen on offshore platforms, PV for remote islands. The combination of market based with technology-based innovation implies that the innovation is radical and disruptive.

2. Goal and purpose

The sea offers space for PV deployment, but there are currently no floating solar farms at open sea, except a 50kW pilot farm 12 km west of Scheveningen, built and operated by Oceans of Energy during the NS1 subsidy project “Zon op Zee”. The power yields of solar at sea, influenced by for example the cooling effects of the water, changing angles due to dynamic wave conditions, high wind speeds, possible salt deposits, algae growth or colonization by invertebrates have not yet been mapped nor compared sufficiently to land modules. Until now, floating solar at sea is an almost unknown application in scientific literature. An early experimental study in Malta was done in which it was concluded that solar at sea can be technically feasible [14]. Other studies have proven that solar at sea is an interesting addition to the renewable energy mix of some countries [15].

From a scientific perspective, as well as economically, it is extremely important to understand the differences in PV performance in various settings. In this project, it was aimed to experimentally assess performance differences between land and sea-based PV systems in a temperate climate zone, thereby adding to existing studies on performance enhancement of floating PV systems on water surfaces in-land, such as lakes and water reservoirs. It has been shown that energy yield of in-shore floating PV systems can be >10% larger compared to installations on land [12].

The central research question addressed in this project is “What is the performance advantage of a floating system at sea compared to a land-based system?”.

Oceans of Energy has developed and scale-tested in the NS1 subsidy project “Zon op Zee” a feasibly design for floating PV offshore system (Figure 1). In the CSEALAND project, Oceans of Energy and UU collaborated to gain scientifically validated insights on the performance in the North Sea, and generic insights to estimate performance benefits at different locations.

Figure 1 *– Photograph of the offshore floating PV system developed by Oceans of Energy in the NS1 subsidy project “Zon op Zee” (TEHE117022) (© Oceans of Energy).*

3. Results

3.1. Platform design and construction

The platform was designed to withstand the conditions in the North Sea during the lifetime of the project, as well as the environmental conditions. Moreover, very specific requirements had to be included to implement the complex monitoring and measurement equipment required for the off-grid test setup. The following principles and components have formed a strong basis for the final design and dimensions of the floating solar platform:

- Metocean conditions of the North Sea, specifically the short and steep waves
- Farm layout of a large floating solar park with multiple, interconnected units
- The design for a mooring system in the North Sea
- Selection of PV technology in the system, intended mounting principles to be tested, indicative cabling and loss calculations

The feasibility of the basic design has been verified by means of activities prior to the NS1 and CSEALAND project using the following methods: (1) Expertise from offshore expert inside and outside OOE's organization; (2) Testing at scale in inshore lakes and basins: the hydrodynamic behavior of the floater alone and in an array of multiple floaters was visually observed; (3) Hydrodynamic simulation (as part of the NS1 Zon op Zee (TEHE117022) project): the design of the mooring facility is configured and simulated with software tools, based on the results of the observations at the scale tests and the metocean conditions of the North Sea.

In the initial project plan, we foresaw the option to equip the floater with different heights and tilts to implement performance optimizations. The consortium needed to move away from this because:

1) Different heights and tilts would make the platform significantly heavier and more fragile, increasing project risks and decreasing the chance of useful results from a year of testing
2) Platform instability and other technical challenges in applying different configurations proved greater than anticipated, creating a risk of further significant project delays
3) The risk arose that the differences in results might be recoverable from having different configurations in one floater rather than the differences between the configurations (e.g. configuration A performs x% better than configuration B, however that is because configuration A negatively affects configuration B such as shade). There would therefore be a risk of erroneous conclusions.

The consortium jointly agreed that the change to an unambiguous height and tilt configuration would not lead to less interesting scientific insights. Instead, it was anticipated that the single configuration would increase the chances of accurate measurements and would reduce the number of factors that could disrupt the experimental set-up.

The design of the power system was done with the help of Victron Energy [16], who supplied several components. A system design was made that allowed the panels to be always at maximum power point, while not being connected to a power grid. This required the use of individual power optimizers and a battery system. The system design was based on the fact that batteries are required to store the energy that is needed to power the measurement equipment such that several days of low irradiance can be overcome, while a large resistive load is required to dump excess power once the batteries are full.

The above combined basic features have resulted in a design of a pontoon on which 12 PV panels can be installed, leaving sufficient space for the monitoring system.

During the construction phase several tests have been performed and several optimizations on tools and the structure have been executed. This included a full deployment floating test at a shipping yard. Functional testing of the floater was performed at UU, which led to some redesign of electronics. While an offshore installation plan has been worked out in detail, the actual installation did not take place, in agreement with RVO. The reasons were a combination of technical, financial and practical reasons.

After this functional testing, a combination of technical, financial, and practical reasons led us to decide not to deploy the floater at sea. we never executed this phase, in agreement with RVO. The objective of the project was to compare the energy yield between the same type of panels placed on land and placed at sea, under the most optimal settings for both locations, and then to compare these field data with a numerical model. The optimal setting for panels at sea (small angle instead of horizontal, with good drainage to optimize the self-cleaning effect, robust panels with frames) was however not realized on the CSEALAND platform. From offshore learnings in the NS1 Zon-op-Zee project, which was ongoing almost in parallel, we realized the CSEALAND platform designed and built in 2018/2019 was no longer up to date with OOE’s improved design. This design had been further developed and greatly improved based on 1.5 year of experience at sea. From the observations of these tested NS1 platforms we concluded that the originalCSEALAND platform concept would not work and would not produce relevant data for making a comparison between optimal performance of the solar panels in both conditions.

Furthermore, The CSEALAND platform has unframed solar panels. These unframed panels did not appear to be able to withstand the wave action experienced at sea with the NS1 platforms. We anticipated the panels would probably be damaged in the first storm and, in the worst case, end up in the marine environment. On top of that, the off-grid battery system of the CSEALAND platform had been (necessarily) changed by UU, in such a way that the new battery no longer fitted in the 'WaterTighBox' (WTB) specially designed and welded for it. The resistors (needed to dump electrical load when batteries are full) were replaced by the UU, as the previous resistors burned out during the onshore control tests. A new robust design for integration of the new resistors into the platform was not available, time and resources permitting. Both UU’s and Oceans of Energy's project budget had been almost completely consumed.

3.2. Performance modeling

A generic mathematical model has been developed for the floating PV system [17]. In the model the following factors have been taken into consideration:

1- The dynamic tilt of panels due to wave induced motion;
2- Relative humidity and wind speed to model the apparent temperature for the panels;
3- Sea water and ambient temperature, and solar irradiance
4- The effect of wind for the computation of the dynamic sea albedo and its effect on the reflective component of the irradiance.

Sea waves are modeled in the frequency domain, using a wave spectrum. The irradiation on a tilted surface for a floating system is calculated considering the tilt angle that is affected by the sea waves. Moreover, the temperature is estimated based on heat transfer theory and the natural cooling system for both floating and land-based photovoltaic systems [18,19]. Actual measured weather data from two different locations, one located at Utrecht University campus and the other one on the North Sea, are used to simulate the systems, thus making the comparison possible. Additional satellite-derived irradiation data was collected from KNMI, which direct and diffuse irradiation at 15-minute time resolution. These data were also used for the modelling. Energy yield is calculated for these weather conditions. To this end, we made use of PVLIB functions in Python that have been developed by the PV performance modelling collaborative, led by Sandia National Laboratories in Albuquerque, NM, USA [20].

The results show that the relative annual average output energy is about 13% higher at sea compared with land. However, in some months, this relative output energy increases up to 18% higher energy yield at sea. The higher output is due to cooling of the panels (about $1/3^{rd}$ *of the energy* yield advantage) in combination with higher irradiance at sea (about $2/3^{rd}$), see for more details [17].

3.3. Land-based test

Figure 2 shows the land-based test system. From data collected over a year, we can conclude that this kind of off-grid system can work to collect data on solar panel performance. The panels were kept at maximum power point, and even in the darkest period of winter the batteries did not run out of power, although battery depth of discharge reached below 10% on December 26th of 2021. At that point any extra loads that would be connected will be shut off to save the battery.

***Figure 2**– Land based PV system, with cabinet for power optimizers, batteries, and energy management system, with dump loads on the back. Local wildlife used it as refuge.*

3.4. Validation

Actual performance difference assessment between the floating system and the land based system could not be carried out, as the floating platform was not installed at sea. As a result, the model results from WP2 could not be validated experimentally.

3.5. Economic assessment

For financial assessments and economic feasibility Levelized Costs of Energy (LCOE) models are used. The LCOE estimates are largely based upon three factors 1) learning rates, 2) scaling factors, and 3) environmental resources.

The results have proven the potential benefits in terms of energy yield for moving solar systems offshore. Based on the modelling studies, these results are used as key drivers in the LCOE model. The model can now be used to estimate yields at different sites worldwide, with varying solar irradiation conditions. The results are above expectation. An increased performance was expected due to cooling of the system, however the upsides for the higher irradiation on the systems were unexpected. The results are now further assessed and tested with the ongoing OOE (Oceans of Energy) projects NS2 (part of DEI+ North Sea Two) and NS3 (part of H2020 EU-SCORES).

4. Discussion

Utrecht University coordinated the project. The cooperation between Utrecht University and Oceans of Energy went well. During the duration of the project, several technical project meetings and work sessions were carried out, which resulted in knowledge transfer.

CSEALAND was an ambitious project with innovative and challenging objectives. Not all of the objectives have been achieved as a result of various issues including the Covid pandemic and unforeseen technical challenges. For instance, the design of the data acquisition and battery management system turned out to be much more difficult than initially assumed, precisely because the floater had to be an off-grid system, which, in case of a full battery, had to dump energy via resistors to the sea. Also, the system had to be self-sufficient for a number of days (in case of consecutive overcast periods), this was an issue also discussed with the supplier of the batteries. Building of the floater also took more time. The consortium regrets that the CSEALAND project has not led to the maximum success for which the project was set up. On the other hand, we are convinced that the CSEALAND consortium has made a successful contribution to the project and TKI UE program objectives. The collaboration led to a few highly acclaimed (and first-in-the-world for offshore solar) scientific publications (even despite Corona). The project has also led to important learnings for OOE to make offshore solar energy possible, which means that with the current technology that is used in the "NS2 project", there is great certainty that the other objectives can also be achieved.

Finally, the offshore deployment of the floater was never realized. This was jointly decided by UU and OOE, and approved by RVO: the initial objective of the project to carry out a comparison of equal systems offshore and on land under the most optimal settings was not feasible with the built floater. Knowledge gained in the NS1 project made that the floater of CSEALAND was deemed not suitable for stand-alone deployment at sea, but only in an array of floaters. Also, the delay due to Covid caused a huge delay. The consortium was not in a position anymore to allocate manpower and budget to modify and complete the CSEALAND platform. The teams had used up the available hourly and materials budget.

5. Follow up activities

The CSEALAND project has managed to realize an offshore PV floater which is estimated to have 13% higher energy yield than a comparative land-based system. It has produced unique results for both project partners.

UU was able to extend its experience in PV performance modelling considerably, which has led to several publications, see section 8. In addition, as UU is national representative in IEA-PVPS Task 13, UU contributed to a report on "*Performance of New Photovoltaic System Designs*" [21], in the floating PV section. In the fall of 2022, the Task 13 will be extended, including a subtask on floating PV systems. Another indirect outcome was that learnings from the CSEALAND project were beneficial for the OOE engineering team who also build the NS1 Zon op Zee floaters. Due to a successful NS1, the follow-up project NS2 with a large consoritium including OOE, UU, TNO, Deltares, WMR, NIOZ, and Marin was funded and started in August 2021. Finally, obtained results are also be implemented in courses for master students at UU. OOE was able to implement the learned lessons of this project immediately in the parallel running project "Zon op Zee" (also called NS1: North Sea 1), Dec 2017-Dec 2021.

The list of learnings within CSEALAND is large and very important. It marked in a sense the birth of offshore solar. This is also visible in the follow-on projects such as NS1, NS2 and EU-SCORES. Oceans of Energy, with partners, was ready to make the "Zon op Zee" NS1 project successful, a first in the world in which floating solar platforms are deployed in high seas.

For almost two years OOE operated an offshore solar farm system of 50kW nearshore and 12 km from the coast; it withstood large storms including Ciara and Dennis in Feb 2020 and OOE was able to collect first data on loads, movement, power output and environmental impact. As a further follow up of this first success the NS2 project was started, which aims to develop a one MW-scale farm as well as carry out studies and impact assessments related to the economic feasibility, production and environmental and social interactions that can be expected for larger offshore solar farms. Even further in the future, a 3 MW-sized farm will be deployed in the Belgium North Sea in two years (EU-SCORES, started July 2021). CSEALAND was the start of this all, it allowed us to tackle important technical challenges related to the design and construction of a robust floating platform supporting photovoltaic panels. It enabled the future of offshore solar, and demonstrated to the world that offshore floating solar is feasible.

6. Dissemination

Dissemination activities have aimed to promote non-confidential results obtained within the project as swiftly and effectively as possible for the benefit of the whole (scientific) community and to avoid duplication of R&D efforts. All modelling work has been presented to the international scientific community as well as nationally.

Published papers

Sara Golroodbari, V. Fthenakis, W.G.J.H.M. van Sark, *Floating photovoltaic systems*, Chapter 1.32 in W.G.J.H.M. van Sark, V. Fthenakis (Eds.) *Photovoltaic Technology,* Volume 1 in T. Letcher (Ed.) *Comprehensive Renewable Energy 2nd Edition,* Elsevier, United Kingdom, 2022, pp. 677-702.

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 219 (2021) 65-74. [Top cited article 2020-2021).

Sara Golroodbari, Wilfried van Sark, *Zonnepanelen op zee, drijvende energiebron van de toekomst,* Nederlands Tijdschrift voor Natuurkunde 86 (9), 2020, pp. 22-25.

S. Zahra Mirbagheri Golroodbari, Wilfried G. J. H. M. van Sark, *Simulation of performance differences between off-shore and land-based photovoltaic systems,* Progress in Photovoltaics 28 (2020) 873 - 886.

Abdulhadi W.A. Ayyad, S. Zahra Golroodbari and Wilfried G.J.H.M. van Sark, *Worldwide Offshore Floating Photovoltaic Yield Assessment: Finding Yield Advantages*, Solar Energy (submitted, 31 December 2020, revision submitted 28 May 2021)

S.Z. Mirbagheri Golroodbari, W.G.J.H.M. van Sark, *On the Effect of Dynamic Albedo on Performance Modelling of Offshore Floating Photovoltaic Systems*, Solar Energy Advances 2 (2022) 100016

Conference contributions

Sara Mirbagheri Golroodbari, Wilfried G.J.H.M. Van Sark, *Implementing Smart Panels to Mitigate Mismatch Conditions for a Dynamic Off-shore Floating PV System*, 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8), Milano, Italy 26-30 September 2022 (submitted, 4 February 2022)

Abdulhadi Ayyad, Sara Mirbagheri-Golroodbari and Wilfried van Sark, Koeppen-Geiger Climate Classification Not a Determinant for the Siting of Offshore Floating Photovoltaics, 37th EU PVSEC Lisbon 7-11 September 2020 (accepted as poster, 6CV.2.34)

S.Z. Mirbagheri Golroodbari, W.G.J.H.M. van Sark, Quantification of the Effect of Albedo Modeling for a Floating PV System on the North Sea, 37th EU PVSEC Lisbon 7-11 September 2020 (oral presentation, 5BO.6.2)

S. Zahra Mirbagheri Golroodbari, Wilfried G. J. H. M. van Sark, *Simulation of performance differences between off-shore and land-based photovoltaic systems,* 36th EU PVSEC, Marseille, 9-13 September 2019 (oral)

S. Zahra Mirbagheri Golroodbari, , *Simulation of performance differences between off-shore and land-based photovoltaic systems*, Grand Cru Award for best Dutch presentation at an international PV conference, Sunday 2019, 13 November 2019, Bussum.

Student reports

Douwe Vaartjes, Techno-economic feasibility of integrating offshore floating solar technology with offshore wind turbines, M.Sc. Thesis Energy Science, supervisors: Johnny Meit (Oceans of Energy), Mattijs Eberveld (Rijkswaterstaat), Prof. Wilfried van Sark (UU), January 2019.

M.A. van den Berg, M. Khandelwal, S. Knibbeler, M.F. Verboon, M.P. Zijlstra, A. Zuiker, *Lessons learned from offshore wind for developing offshore PV*, report for Consultancy Project, Master Energy Science, Utrecht University, June 2018.

PR of project and further PR possibilities

The project partners would like to be approached for any further publicity activities and would like to contribute to public activities of the Rijksdienst voor Ondernemend Nederland or the TKI-Urban Energy and are happy to add these insights to the debate about the energy transition in the Netherlands.

References

[1] IPCC, Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, Cambridge, 2011.

[2] IEA, World Energy Outlook 2020, International Energy Agency, Paris, 2020.

[3] IRENA, Global energy transformation; a roadmap to 2050, International Renewable Energy Agency, Abu Dhabi, 2018.

[4] DNE Research, Nationaal Solar Trend rapport, 2022.

[5] B. Den Ouden, J. Kerkhoven, J. Warnaars, R. Terwel, M. Coenen, T. Verboon, Klimaatneutrale energiescenario's 2050; Scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050 (Climate neutral energy scenarios 2050; scenario study for the integral infrastructure outlook 2030-2050), Berenschot/Kalavasta, Utrecht, 2020.

[6] 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 219 (2021) 65-74.

[7] W. Folkerts, W. van Sark, C. de Keizer, W. van Hooff, M. van den Donker, ROADMAP PV Systemen en Toepassingen (ROADMAP PV Systems and Applications), SEAC, Utrecht University and TKI Urban Energy, 2017.

[8] W. van Hooff, T. Kuijers, R. Quax, J. Witte, M. Londo, J. Matthijsen, W. van Sark, W. Sinke, Ruimtelijk potentieel van zonnestroom in Nederland, TKI Urban Energy, 2021.

[9] D. Keiner, O. Salcedo-Puerto, E. Immonen, W.G.J.H.M. van Sark, Y. Nizam, F. Shadiya, J. Duval, T. Delahaye, A. Gulagi, C. Breyer, Powering an island energy system by offshore floating technologies towards 100% renewables: A case for the Maldives, Applied Energy 308 (2022) 118360.

[10] World Bank Group, ESMAP, SERIS, Where Sun Meets Water: Floating Solar Handbook for Practitioners, Washington, DC: World Bank, 2019.

[11] Z. Wang, R. Carriveau, D. S.-K. Ting, W. Xiong, Z. Wang, A review of marine renewable energy storage, International Journal of Energy Research 43 (2019) 6108 – 6150.

[12] K. Trapani, M. Redón Santafé, A review of floating photovoltaic installations: 2007–2013. Progress in Photovoltaics: Research and Applications 23 (2015) 524-532.,

[13] Y. Choi, A study on power generation analysis of floating PV system considering environmental impact, International Journal of Software Engineering and its Applications 8 (2014) 75-84.

[14] M. Grech, L. Mule Stagno, M. Aquilina, M. Cadamuro, U. Witzke, Floating photovoltaic installations in maltese sea waters, Proceedings 32nd EU PVSEC, Munich, 2019, pp. 1964-1968.

[15] M.Z. Jacobson, M.A. Delucchi, Z.A.F. Bauer, S.C. Goodman, W.E. Chapman, M.A. Cameron, C. Bozonnat, L. Chobadi, H.A. Clonts, P. Enevoldsen, J.R. Erwin, S.N. Fobi, O.K. Goldstrom, E.M.

Hennessy, J. L, J. Lo, C.B. Meyer, S.B. Morris, K.R. Moy, P.L. O'Neill, I. Petkov, S. Redfern, R. Schucker, M.A. Sontag, J. Wang, E. Weiner, A.S. Yachanin, 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World, Joule 1 (2017) 108 – 121.

[16] Victron Energy, https://www.victronenergy.nl

[17] S. Zahra Mirbagheri Golroodbari, Wilfried G. J. H. M. van Sark, *Simulation of performance differences between off-shore and land-based photovoltaic systems,* Progress in Photovoltaics 28 (2020) 873 - 886.

[18] M. Rosa-Clot, P. Rosa-Clot, G. Tina, P. Scandura, Submerged photovoltaic solar panel: SP2, Renewable Energy 35 (2010) 1862-1865.

[19] E. Skoplaki, J.A. Palyvos, On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations, Solar Energy 83 (2009) 614–624.

[20] PV performance modelling collaborative, https://pvpmc.sandia.gov.

[21] M. Littwin, F. Baumgartner, M. Green, W. van Sark, *Performance of New Photovoltaic System Designs*, IEA-PVPS, Report number IEA-PVPS T13-15: 2021, April 2021, ISBN: 978-3-907281-04-8. (https://iea-pvps.org/wp-content/uploads/2021/03/IEA-PVPS_Task-13_R15-Performance-of-New-PV-system-designs-report.pdf)