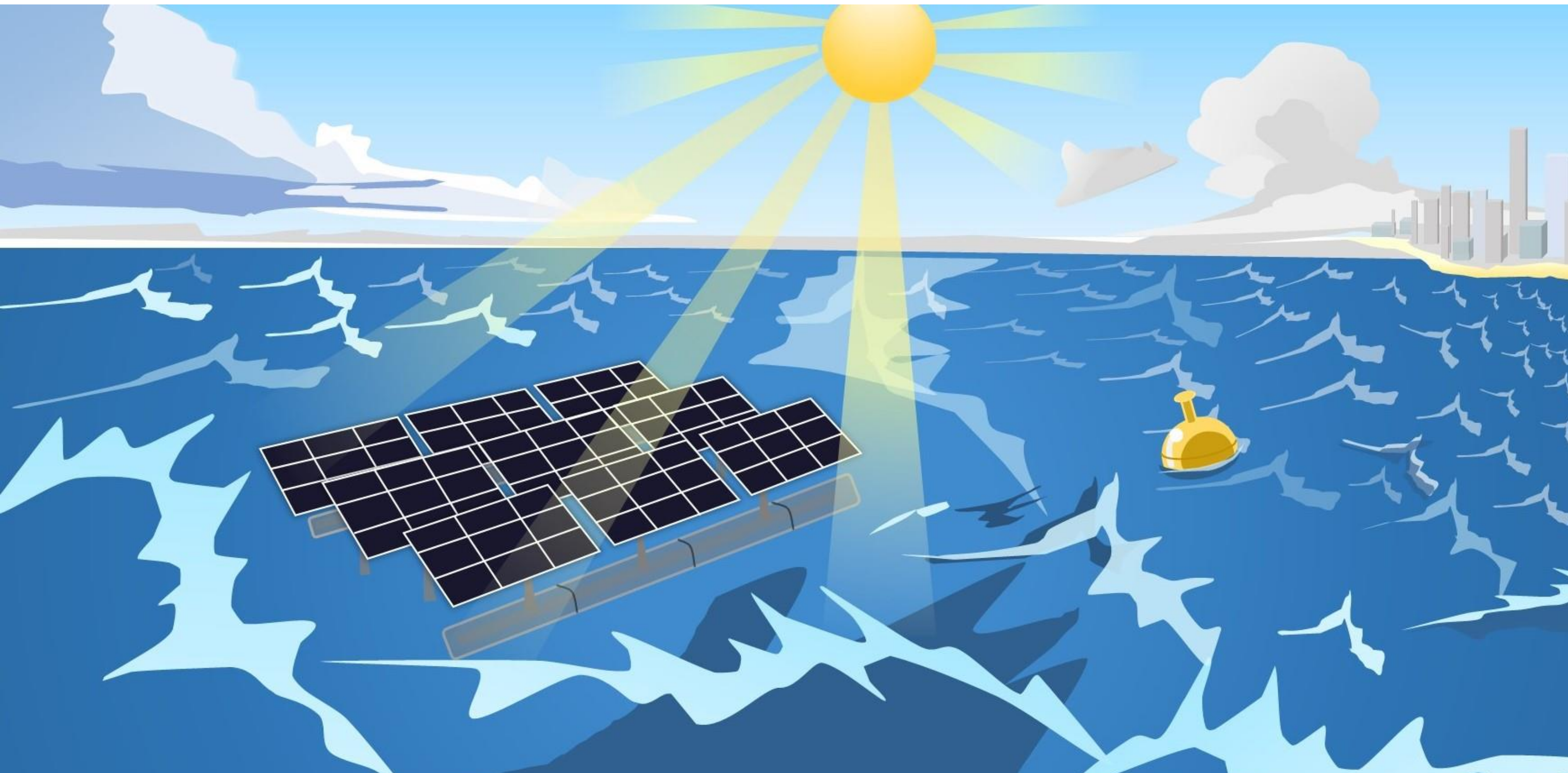
Implementation of Floating Photovoltaics in the German Marine Space

- Feasibility, Potentials and Barriers for the Multi-Use of Marine Space of the North Sea for Renewable Offshore Energy

Sina Aline Berends | S5335663 | 17.10.2023



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Abstract

This thesis analyses the opportunities and advantages, the spatial potential, and barriers to the multi-use of marine space and energy infrastructure of the German North Sea when integrating floating photovoltaics into offshore wind farms.

Transition theory and the concepts of marine spatial planning and ocean multi-use provide insights for this thesis. Floating photovoltaics (FPV) in a multi-use context is considered a niche innovation in a transition with the potential to challenge the regime. To answer the research questions, a literature review and semi-structured interviews were conducted with experts from the field, namely technology developers, technology accelerators, science and research, and a German permitting authority.

The results show that the technology of offshore floating photovoltaics is not mature yet due to technical and financial constraints. Besides that, there are many advantages to the innovation of offshore FPV in a multi-use context, especially in wind farms due to overlapping spatial, temporal, and provisioning dimensions between offshore floating photovoltaics and offshore wind energy, with the opportunity to share energy infrastructure and thus increase the capacity of the grid and reduce costs. When integrating floating photovoltaics in those wind farms, a greater share of the area can be covered and thus the energy density increases. The results indicate a great spatial potential for the innovation in Germany, because of many existing and planned wind farms and reserved areas for wind farms that occupy much of the German marine space. However, the technology is not ready yet for large-scale implementation and the environmental effects are not thoroughly known. Furthermore, institutional, financial, and political barriers occurred, as well as barriers due to lack of data.

Overcoming barriers to implementing offshore floating photovoltaics in a multi-use context requires several measures. Key recommendations include dedicating space for FPV testing and pilot projects to accelerate technology development. Financial support is also important to create viable business cases. Furthermore, the specification of targets can give certainty and lift barriers. Regulatory and institutional changes are also inevitable, changes in the tendering system for wind farms, joint licensing procedures and answering regulatory questions are decisive for scaling the innovation and promoting multi-use to challenge or enhance the current regime of marine spatial planning. Certainly, for all the recommendations, political awareness and support are key and should therefore be improved. Lifting barriers in Germany must also include studying how multi-use is possible and generally, further research is suggested to remedy the lack of data, also regarding environmental effects. To accelerate the change, regulations from other sectors or other countries, like the Netherlands, should serve as role models for German regulations. Overall, transboundary collaboration and exchange can help accelerate development.

Keywords: Marine Spatial Planning, Multi-use, Offshore Floating Photovoltaics, Renewable Energy, Energy Transition, German North Sea

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Abbreviations

BSH = Bundesamt für Seeschifffahrt und Hydrographie/The Federal Maritime and Hydrographic Agency

EEG = Erneuerbare-Energien-Gesetz/Renewable Energy Source Act

EEZ = Economic Exclusive Zone

EU = European Union

FPV = Floating Photovoltaics

GW = Gigawatts

LCOE = Levelized Cost of Energy

MSP = Marine/Maritime Spatial Planning

MU = Multi-Use

NIMBY= “Not in my backyard”

OWE = Offshore Wind Energy

OWF = Offshore Wind Farms

PV = Photovoltaics

UBA = Umweltbundesamt/German Federal Environment Agency

1. Introduction

Germany is situated in the middle of its energy transition called "Energiewende" and its nuclear phase-out as well as a targeted coal phase-out by 2038. The aim is clean, secure and affordable energy with climate neutrality by 2045 (Federal Ministry for Economic Affairs and Climate Action, n.d.). Therefore, 80 % of gross electricity consumption should be covered by renewable energies by 2030. To meet the targets, the current shares of renewables in electricity production (46.2% in 2022) have to almost double in the next eight years, requiring a tripling of the implementation speed of wind and solar farms (Die Bundesregierung, n.d.). This poses a problem because the energy density of renewables is significantly lower than that of conventional fossil fuels. As a result, renewables require much more space to produce the same amount of energy (Layton, 2008) and much space is needed to reach the German goals. But space is scarce, so there is competition for it (van Hoof, van den Burg, Banach, Röckmann, & Goossen, 2020). The competition does not end at the shore, as ocean space is also under competition. The competition for space resulted in the introduction of Marine Spatial Planning (MSP), and European countries were advised to create a marine spatial plan for their country. MSP is a tool to manage conflicts between uses to achieve societal goals (Schupp et al., 2019). MSP is evaluating and designating portions of marine areas for particular purposes, intending to attain ecological, economic, and societal goals typically delineated through the political decision-making process (Ehler & Douvere, 2007). Despite MSP being an integrative concept, single-sector management is the norm where co-location and multi-use is the exception (Schupp et al., 2019). Building on this, the relatively new multi-use approach introduces multi-sector management (ibid). 'Multi use' (MU) is considered a "joint use of resources in close geographic proximity". (Definition of MUSES Project) (Przedrzymirska, 2018). Multi-use means sharing a resource which can be, among others, space (Przedrzymirska et al., 2018). Efficient use of (ocean) space maximises the economic benefit from a certain area, reduces the environmental impact and leaves areas for future generations (Schultz-Zehden, Lukic, Ansong, Altvater, Susanne, Amlett, Rebecca, & Barbanti, 2018).

In 2021, Germany published the newest marine spatial plan (European MSP Platform, 2022). It shows the domination of single-use, as opposed to multi-use, and due to the urgent energy transition, much area is designated for wind energy (cf. ibid). It also shows that there are few areas left to introduce new uses. This illustrates the need for multi-use in the German North Sea. To meet the targets of the German energy transition and eventually become carbon-neutral by 2045, the current offshore wind farms (OWF) and their capacity as well as the implementation speed is not enough (Hummel, 2023) Therefore, new technologies should be implemented in addition to offshore wind farms because alternative technologies for energy generation offer promising solutions to increase the capacity. One emerging technology is called floating photovoltaics (FPV) that started on freshwater reservoirs and therefore onshore but was further developed so that they are now used offshore in the first pilot projects in the North Sea (Frangoul, 2022; Oliveira-Pinto & Stokkermans, 2020). The current floating solar capacity reaches 50 kW in the EU (Borriello et al., 2023). The technology emerged because of land scarcity, energy security, aims towards decarbonization and the loss of efficiency of PV modules when the cell temperature becomes too high in operation (Oliveira-Pinto & Stokkermans, 2020). This new technology can share space with offshore wind farms because the space in between the wind turbines can be used for floating photovoltaics (López, Rodríguez, & Iglesias, 2020). A combination of harvesting wind and solar radiation increases the generated energy per area and thus the energy density (ibid). For offshore FPV and OWF, joint use of energy infrastructure is also possible, which makes a multi-use cost and resource-efficient (Crosswind, 2023; López et al., 2020). Solar and wind are complementary resources with an anti-correlation. In winter, there is more wind but less sun; in summer, there is more sun but less wind (RWE Offshore Wind, n.d.). Consequently, with the so-called cable pooling, cables can be shared by the different power plants and thus a more balanced energy production profile with a more stable energy supply is provided and the utilization of the grid infrastructure can be increased (Golroodbari et al., 2021; Ocean of Energy, 2019; RWE Offshore Wind, n.d.). The correlation is visible in Figure 1. The graphic shows a simulation of a system with 100 MW offshore wind and 100 MW offshore solar installed at the North Sea site per month in 2020 (EU-SCORES, 2022). It shows that only little electricity is curtailed when combining wind farms with offshore floating photovoltaics and that the addition of FPV can help generate a more stable energy output throughout the year.

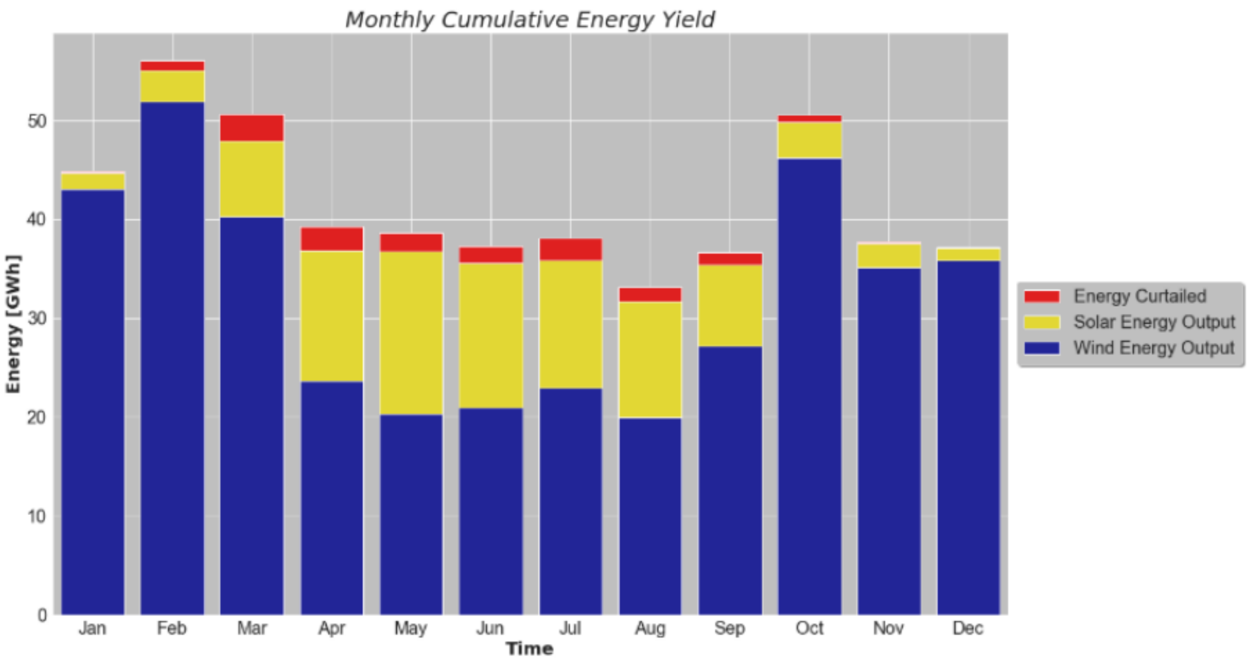

Figure 1: Simulation of a system with 100 MW offshore wind and 100 MW offshore solar installed at the North Sea site per month in 2020. Simulation by Oceans of Energy. Source: EU-SCORES, 2022.

However, despite the promising characteristics of offshore floating photovoltaics, there is no implementation in Germany's economic exclusive zone (EEZ) yet (cf. European MSP Platform, 2022). As the technology is currently being developed and improved to meet the rough conditions of the North Sea (Snieckhus, 2019), ecological, and economic impacts have yet to be determined. When all the conditions of technical, economic, and ecological feasibility are fulfilled, questions of institutional opportunities and barriers must be answered to ensure fast implementations as soon as technical maturity is given.

There is a rising amount of literature about multi-use and the different combinations of sectors. Also, there is growing research about floating photovoltaics. Nevertheless, there is little literature investigating the combination of floating photovoltaics and offshore wind farms for the multi-use of the ocean, especially in Germany. This thesis contributes to increasing knowledge and complementing the current literature.

The results of the study can be valuable for marine spatial planning in Germany and the expansion of renewable energies. Analysing the German marine spatial plan and the opportunity of combining offshore wind farms and floating photovoltaics, it is important to understand the spatial potential of the technology to indicate the potential for change to achieve energy and carbon targets. Additionally, it helps to understand what must change for large-scale implementations of floating photovoltaics across the German North Sea.

The academic relevance of this research is given by the aspects of the scarcity of space, the renewable energy transition, and the investigation of the relatively new topic of floating solar farms, which currently emerges in the academic debate. This research adds to an understanding of the potential to use the already crowded marine space efficiently with new technologies and which barriers can limit the implementation of ocean multi-use and new offshore technologies.

Societal relevance is also given by space scarcity and the current dominance of single use of space in the German North Sea. The efficient use of marine space for renewable energy generation facilitates reaching the Energy transition targets (Stelzenmüller, 2022). This thesis investigates the institutional factors that shape the implementation of multi-use in the current MSP, analyses the spatial potential of offshore floating photovoltaics and aims at finding ways to multi-use energy infrastructure to increase the energy density with a spatial combination of technologies and the opportunity to leave space free for other uses.

For planning practice, the results help to plan the energy transition with new emerging technologies and to identify and overcome institutional barriers. Planning practitioners should know if and to what extent multi-use of energy infrastructure and space is possible for floating photovoltaics and offshore wind farms in the German North Sea. The study aims to enlighten the relatively new technology and the steps that are necessary to successfully implement it. The resulting spatial potential is a direct and valuable output for marine spatial planning practice.

In the following thesis, I will analyse the opportunities, (spatial) potentials and barriers to the integration of floating photovoltaics into existing and upcoming offshore wind farms in the German North Sea. The main research question is thus:

What are the opportunities, what is the spatial potential, and what are the barriers to the multi-use of marine space and energy infrastructure of the North Sea when integrating floating photovoltaics into offshore wind farms?

The sub-questions are:

I. *What is the current state of technology for offshore floating photovoltaics and what are its advantages in comparison to onshore installations or other technologies?*
II. *What are the advantages and opportunities of a combination of offshore floating photovoltaics and wind farms in a multi-use context and what is important to consider in planning?*
III. *What are the requirements for implementations in the German EEZ and what is the (spatial) potential of a multi-use of space and energy infrastructure of floating photovoltaics and offshore wind farms in the German North Sea?*
IV. *What are (potential) barriers (in Germany) to implementing floating photovoltaics on the integration into offshore wind farms?*
V. *How could barriers be overcome?*

Considering the sub-questions and the concepts of marine spatial planning and multi-use tailored to the German case, the thesis is structured as follows. In chapter two the theoretical framework is displayed where an introduction to marine spatial planning (MSP), transition theory, and multi-use and offshore floating photovoltaics is given. Afterwards, in chapter 3, the German case is presented with the German energy transition, the legislation and responsibilities and the maritime spatial plan. Following is the methodology where the methods are displayed and the selection justified. In chapter 5 the results are presented. In chapter 6 the presented results are discussed, and a conclusion is drawn followed by a final reflection at the end.

2. Theoretical Framework

In this chapter, the main theories for this thesis are presented. Starting with marine spatial planning, followed by transition theory and the multi-use concept. Afterwards, the theory of offshore floating photovoltaics is introduced. Lastly, the conceptual model is presented.

2.1. Marine Spatial Planning

Marine spatial planning becomes necessary due to growing competition for space (Boussarie, Kopp, Lavialle, Mouchet, & Morfin, 2023). MSP is an approach to managing the use of marine space in a way that is coordinated, integrated, and sustainable and aims to promote sustainable development, reduce conflicts, and enhance ecosystem services in marine environments. It is designed to balance the competing demands and interests in these areas, such as conservation, fishing, shipping, tourism, energy production, and environmental protection. Therefore, it organizes the ocean space as well as human interactions (Frazão Santos et al., 2018). It is a relatively new field, with the first publications published in 2007 (Ehler, Zaucha, & Gee, 2019).

Marine Spatial Planning is defined by the UNESCO/IOC as: *„The public process of analyzing and allocating the spatial and temporal distribution of human activities to achieve ecological, economic, and social objectives that are usually specified through a political process."* (Ehler & Douvere, 2009, p. 24).

To ensure that every EU country located at the coast has a marine/maritime spatial plan, the EU issued the EU MSP directive in 2014. It stated that all countries had to draw up a marine spatial plan by 2021. Among other things, that directive required member states to apply an eco-system-based approach and to promote the co-existence of activities (Ronco, 2018). The definition of MSP by the directive reads as: "*A process by which the relevant Member State's authorities analyse and organise human activities in marine areas to achieve ecological, economic and social objectives."* (THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION, 2014). According to the EU directive, the maritime spatial plans of Member States should aim to achieve sustainable development in various sectors, including energy, maritime transport, fisheries, and aquaculture. They also focus on preserving, protecting, and enhancing the environment, with a particular emphasis on building resilience to climate change impacts (ibid). Therefore, current, and future activities are managed through MSP. Among the main objectives of marine spatial planning in the European Union is "protecting the environment by assigning protected areas, calculating impacts on ecosystems and identifying opportunities for multiple uses of space" (Directorate-General for Maritime Affairs and Fisheries, n.d.).

Germany already has a maritime spatial plan since 2007 that was reworked and newly published in 2021 to adapt it to the new needs of meeting the EU directive and accelerate the energy transition.

In marine spatial planning, single-use areas are predominant (Schupp et al., 2019). Occasionally there is the co-location of uses, for example, the simultaneous use of space for offshore wind farms and fisheries in Germany (ibid).

2.1.1. Marine Spatial Planning and Maritime Spatial Planning: Understanding the Difference

Marine and maritime spatial planning are two terms that describe the organisation and management of ocean space (Ehler et al., 2019). Sometimes those two terms are used interchangeably (as in Ehler, Zauche & Gee, 2019) but sometimes a differentiation is made. For this specific thesis, the differentiation is neglectable and only mentioned because in Germany the spatial plan for the sea is called a maritime spatial plan, although previously the notion of the marine spatial plan was used.

2.2. Transition Theory

The shift to a new energy system with renewable energies instead of fossil ones can be seen as a transition. For transitions, much research has been done to understand how new technologies spread and which factors are supporting or limiting. Within the energy transition, the expansion of support for renewable energy gains importance (Huh, Yoon, & Chung, 2019). Offshore floating photovoltaics in the context of multi-use space can serve as a niche innovation and as a means for the transition towards carbon neutrality and it is thus valuable to understand the mechanisms of transitions and how the implementation of FPV can be facilitated based on this theory.

Transition theory emphasizes the fundamental shift from one socio-technical system to another (Meadowcroft, 2009). It emphasizes the importance of multiple actors, networks, and institutions in driving change, as well as the need for policies that create enabling conditions for new technologies and practices to emerge (ibid). Transition theory adopts a multi-level perspective that considers interactions between different levels of a socio-technical system: the landscape level, the regime level, and the niche level. (Loorbach & van Raak, 2006). The landscape represents the broader socio-economic, political, and cultural context, the regime includes the dominant rules, norms, and institutions, while the niche refers to the space for emerging innovations (ibid).

Transition theory suggests that niches play a crucial role in driving transitions by allowing the exploration and experimentation of new ideas and technologies (Fryszman, Carstens, & Da Cunha, 2019). Established energy regimes, dominated by fossil fuels, often exhibit resistance to niche innovations that challenge their dominance (Geels, 2014). Applying the transition theory perspective to offshore floating PV in the context of multi-use can initially be seen as a niche innovation within the broader energy landscape and the dominant modes in marine spatial planning. Transition theory highlights the need to protect and nurture niche innovations by creating favourable conditions, such as supportive policies, financial incentives, and stakeholder engagement (Geels, 2014). As Schot and Geels (2008) depicted, niches and their innovations are important, but their diffusion is dependent on the linkage with ongoing processes at the landscape and regime levels. Therefore, the diffusion of new energy technologies from niches is only possible within suitable regimes, for example, the ongoing energy transition. However, important to note is that niche innovations do not always try to compete with the existing regime but can also be adopted to solve certain problems (Raven, 2006). Furthermore, niches need windows of opportunity to arise (Schot & Geels, 2008). Those windows occur when the established regime cracks (ibid). Translating into the case of offshore FPV, it shows that an opportunity might occur due to cracks in the established energy system due to climate change and the urgency to become carbon neutral. Simultaneously, the regime of single-use in MSP can create windows of opportunity for the multi-use context due to the scarcity of space. Lessons can then be learned from transition theory to promote the multi-use of oceans (for different renewable energies) and to establish it as a new regime or to solve the problem of space scarcity of the established regime and therefore may not compete with MSP but add value and eventually reconfigure the system substantially (Raven, 2006).

Transition theory emphasizes the importance of governance and management strategies to facilitate and guide societal transitions. It calls for proactive interventions to steer the system towards sustainability (Geels, 2014). Applying transition management to offshore floating PV in a multi-use setting involves designing and implementing policies, regulations, and incentives that support the technology's development, addressing potential barriers, and actively involving relevant stakeholders in the decision-making process (ibid).

The results of this thesis show how supportive the current system is to nurture and facilitate the implementation of floating photovoltaics in a multi-use surrounding and what change might be necessary to further strengthen the transition towards a renewable energy system with FPV and multi-use as a means to reach the targets.

2.2.1. Prominent Barriers to Transitions

In transitions, there are always barriers that complicate the transition towards a new system. Maswabi, Chun, and Chung (2021) analysed the barriers to an energy transition with the development of solar energy in Botswana and came up with different barriers on the different levels of the socio-technical system. Understanding barriers to transitions elsewhere helps to understand the nature of occurring barriers, allows conclusions to be drawn about other cases and shows which barriers might be interesting to investigate in other cases, such as FPV in Germany. Most of the barriers identified by Maswabi et al. (2021) were based on the regime level. At the landscape level, the lack of commitment by policymakers was identified in the Botswana case. On the regime level, the occurred barriers were broken down into the four sub-categories policy and regulation, governance, technical capacity, and finance barriers. At the niche level, the occurring barriers were the lack of funding for research and development and inadequate and unreliable statistical data (Maswabi et al., 2021).

2.2.2. From Transition Theory to Research Emphases

From transition theory emerges the necessity to analyse the institutional framework of the current regime because the regime needs to provide the (legal) frame for niche innovations to thrive (Schot & Geels, 2008). Institutions are described by Beunen and Patterson (2019) as norms and rules in social interactions that guide organizational and human behaviour while Raven et al. (2019) define institutions as “regulative, normative and cultural-cognitive elements that, together with associated activities and resources, provide stability and meaning to social life”. Hereby, the regulative elements are formal rules such as laws and policies (Raven et al., 2019). In general, institutions include laws, procedures, and regulations (Meijer & van der Krabben, 2018). Concurrently, the institutional framework might hinder the thriving of innovations and therefore appear as a barrier (Maswabi et al., 2021). Geels (2014) highlights the importance of addressing barriers to facilitate transitions. For analysing the German case and the opportunities and barriers to the multi-use of ocean space for renewable energies, institutions are therefore important to analyse and uncover and address barriers that (could) currently hinder the implementation of floating photovoltaics in a multi-use surrounding offshore wind farms is crucial.

The existing landscape and the regime, here the German energy landscape, the maritime spatial plan and existing laws and regulations regarding the use of ocean space and offshore renewable energies, are jointly responsible for providing a framework for upcoming innovations and are therefore to investigate. Whether there is physical space where a new technology would have a chance to be implemented is also related to the existing regime and landscape. Therefore, these factors shape the spatial potential.

For an innovation to be implemented, factors like technological maturity and ecological effects are important. The existing regime in the European Union, particularly in Germany, has a strong focus on the environment and the prevention of harm to it (Umweltbundesamt, 2010). Therefore, new technologies need to meet the requirements of leaving no damage to the environment to have a chance of occupying a place in the existing regime as a niche and eventually emerging to possibly more than a niche innovation. Accordingly, the environmental impact and ecological effects of an innovation are important for its success and need further investigation.

Overall, offshore floating photovoltaics in a multi-use context can be seen as a niche innovation. Multiple factors are important and determine the rise of those innovations. Therefore, following Geels (2014), the existing institutional framework (regime) must be analysed, and barriers need to be addressed. The existing regime of maritime spatial planning with single-sector management as the norm is shaping the spatial potential of and barriers to the rising technology of FPV. However, it is also clear that the effects on the environment and technological maturity are important for (technical) innovations to arise from the niche. Thus, the environmental impacts and technical maturity are significant indicators for the success of an innovation in Germany and are therefore decisive values in this research. Following Maswabi et al. (2021), financial barriers might also occur and are therefore further investigated.

2.3. Multi-use Concept

There is a growing body of theoretical literature on the multi-use of space, as well as for renewable energy. Multi-use is a promising concept with various advantages, but also many challenges that need to be addressed. The concept of multi-use emerged as a result of marine spatial planning and the realisation that space is scarce (Przedrzymirska et al., 2018). Accordingly, multi-use is seen as a solution for space scarcity (ibid).

One definition of multi-use used by Schupp et al. (2019, p. 4) is the following:

"Ocean multi-use is the joint use of resources in close geographic proximity by either a single user or multiple users. It is an umbrella term that covers a multitude of use combinations in the marine realm and represents a radical change from the concept of exclusive resource rights to the inclusive sharing of resources and space by one or more users."

One big project dedicated to the research on multi-use is the MUSES project, which was finished in 2018 (Schultz-Zehden et al., 2018). MUSES stands for Multi-Use in European Seas (ibid). The used definition of MU by the projects reads:

"Multi-use (MU) is an intentional joint use of resources in close geographic proximity. It represents a radical change from the concept of exclusive resource rights to the inclusive sharing of resources by one or more uses" (Schultz-Zehden et al., 2018, p. 10).

According to Przedrzymirska et al. (2018), there are three main reasons for multi-use. The first reason is research and innovation that encourage the development of new technologies that provide new ways to use marine resources and improve conservation measures. Secondly, the business itself is a reason and lastly, the scarcity of space validates multi-use. MU can increase the efficiency of the use of space because multiple activities can be in the same area without competing (Schultz-Zehden et al., 2018). Secondly, with more efficient use of space, for example for renewable energy, more space is left for other activities and usages (ibid).

Multi-use can mean not only sharing space but other resources, as the definition of multi-use by Schupp et al. (2019) shows. For their paper, they used four dimensions of connectivity to describe four different forms of ocean multi-use. The four dimensions of typology by Schupp et al. (2019) are also used by the MUSES project and consist of the spatial, temporal, provisioning and functional dimensions. From the four dimensions for multi-use, four types of multi-use were then identified, which have different characteristics and should be treated differently. The first type is the multi-purpose/multi-functional type where all dimensions overlap. The resulting is a multi-use where two or more uses take place in the same area at the same time that shares core infrastructure and services, for example, marine renewable energy sources and salinisation (Schultz-Zehden et al., 2018; Schupp et al., 2019). The second type has every dimension except for the functional one and is called “Symbiotic use”. Therefore, the multi-use takes place in the same area at the same time, but only peripheral infrastructure or services are shared. An example of the second type is aquaculture in areas with offshore wind farms. The third type is “Co-existence/Co-location” and is characterized by spatial and temporal overlaps, for example, fisheries in offshore wind farms. Lastly, the “subsequent use/repurposing” type is only characterized by sharing the spatial dimension. An example is the repurposing of offshore structures (Schupp et al., 2019).

For every type of multi-use Schupp et al. (2019) and Schultz-Zehden et al. (2018) suggest different measures in terms of policies, regulations, research and industry. Therefore, the multi-use type of offshore floating photovoltaics and offshore wind farms must be determined to adapt the recommendations for policy and MSP makers in Germany but also to analyse which policy and regulation instruments are already in place and how the status of current research and industry players is to compare the status quo with the desired status for a successfully implemented multi-use.

Multi-use can be categorized into two types of development (Przedrzymirska et al., 2018). The first type is where at least two combined uses are applying for licences simultaneously. This type is called “Joint development of uses”. Secondly, “Staggered development of uses” describes the development where an emerging use can be combined with and added into a place where there already exists another use (ibid). For offshore floating photovoltaics and offshore wind farms, there might be different planning processes and difficulties as well as advantages when there is either a joint planning process or a later addition of offshore FPV into OWF. This thesis thus also investigates the planning process of a multi-use of space for renewable energy and gives recommendations for planning practitioners.

2.3.1. Drivers, Barriers, and Recommendations for Multi-Use

Drivers for multi-use development are market and policies that can be supported by research and development (Przedrzymirska et al., 2021). The market serves as a force behind the multi-use development because there are economic benefits gained from the combination of uses e.g., lower costs or extra revenues (ibid). The role of policies for the development of multi-use is due to the obligation of maintaining a good environmental status or the support of industries (ibid). Furthermore, space-intensive sectors might gain a higher social acceptance when forcing space-intensive sectors to share space which is also beneficial for policymakers (ibid).

The MUSES-project was finished in 2018 when offshore floating photovoltaics were not popular but other ocean multi-uses for renewable energy promising. The barriers to the multi-use of those renewable energies were investigated. According to these results, the barriers to multi-use implementation are less of a technical nature but more related to separate regulatory and permitting processes as well as different tariff rates and the lack of incentive schemes that result in limited competitiveness of the renewable energy MUs (Schultz-Zehden et al., 2018). Following Onyango et al. (2020), multi-use barriers are mostly of policy, regulatory and socioeconomic nature due to sectoral thinking, complex administrative procedures due to separate permitting for every use, risk liability, legacy costs, and the lack of MU-friendly policies. According to their findings, the opposing factors influencing the adoption of MU were evenly matched, resulting in a lack of discernible advantages for MU (Onyango et al., 2020).

As indicated by the results of the MUSES project, there are some cross-cutting issues and actions that determine a successful multi-use that are interlinked. In multi-use, there are not only two or more sectors involved but also a growing number of actors, regulatory bodies, insurance, finances and stakeholders (Schultz-Zehden, 2018). Furthermore, for new technologies not only the technological status is determining for implementation but also various other factors. These factors can be about regulation, financing, liability issues, environmental concerns, stakeholder perceptions or capacity building (Onyango et al., 2020; Schultz-Zehden, 2018). Another challenge is the need for more research on the environmental impacts of multi-use because the cumulated environmental impact of two or more usages in multi-use can be complex and difficult to predict (Schultz-Zehden et al., 2018). This complicates the permission based on the environmental assessment.

Recommendations to solve the issues and facilitate MU are various. Schultz-Zehden et al. (2018) conclude that a paradigm shift is necessary to advance the development of multi-use that involves the willingness of policymakers, governmental authorities, businesses, investors, and other actors. One major challenge is the need for clear regulations and planning frameworks, also because multiple activities need to be coordinated simultaneously to avoid conflicts. Onyango et al. (2020) concluded three objectives, drawing upon insights from the North Sea. These objectives encompass firstly, integrating MU into crucial policy documents, secondly, assessing the current state of MU application, identifying barriers, and identifying opportunities for future expansion; and lastly, deriving significant lessons and insights to facilitate the promotion of MU (Onyango et al., 2020).

This thesis follows the recommendations by Onyango et al. (2020) by assessing the current state of MU in Germany, identifying barriers and opportunities and deriving lessons and insights for eventually promoting the implementation of multi-use, especially for offshore floating photovoltaics in wind farms. The status quo for the German North Sea must be analysed to give recommendations for future actions of German policymakers to facilitate ocean multi-use, especially for offshore energy production.

2.3.2. Difference between Co-Location and Multi-Use

As mentioned above, the Marine Spatial Planning Directive of the EU stipulates that co-location of uses should be promoted by the countries concerned. It is therefore important to clarify that there is a difference between co-location and multi-use. As indicated by Schupp et al. (2019), co-location is only characterised by spatial and temporal overlaps, for example, when space is used by offshore wind farms and fisheries. Co-location aims at minimising conflicts while maximising benefits. Multi-use on the other hand aims, at least for types one and two of Schupp et al.'s categorization, at the interaction between different uses. This leads to more efficient use of space but also to more complexity. To sum up, while co-location is promoted and supported by the EU's law, a deeper multi-use is not yet made into official guidelines. Therefore, the adoption of a more complex multi-use is voluntary for EU members.

2.4. Introducing the Technology of Offshore Floating Photovoltaics

The technical specifications of offshore floating photovoltaics and their differences from other, established, technologies are important for understanding the significance of that new emerging technology and its current technological status. This allows conclusions to be drawn about why the technology has its current prevalence, what potential it has, and ultimately, its dissemination can be promoted.

Worldwide, photovoltaics is a very successful and relatively cheap, mature and economically feasible renewable energy source (Oceans of Energy, n.d.). However, constraints in space limit the implementation onshore. One solution is to use the vast solar resources offshore with offshore floating photovoltaics (RWE Offshore Wind, n.d.). Locating photovoltaics into water offers efficiency improvements compared to onshore photovoltaics due to a lesser cloud cover and constant cooling (Dana, 2018) as onshore photovoltaics are limited in their efficiency due to heat that lowers the efficiency when the solar irradiance is too high (Dana, 2018; IRENA, 2021). Overall, the efficiency of offshore PVs is on average 13 % more efficient than solar on land (ibid). Further advantages are low visual impact, the usage of abundant resources and the opportunity to be highly scalable (RWE Offshore Wind, n.d.). Furthermore, new markets can be unlocked (ibid).

Floating photovoltaics are photovoltaic modules that are installed on a platform/substructure that floats. The floating platform is held in one position by mooring lines that are connected to anchors (see Fig. 2). The energy transmitted by the technology is transmitted via subsea cables to the shore (RWE Offshore Wind, n.d.).

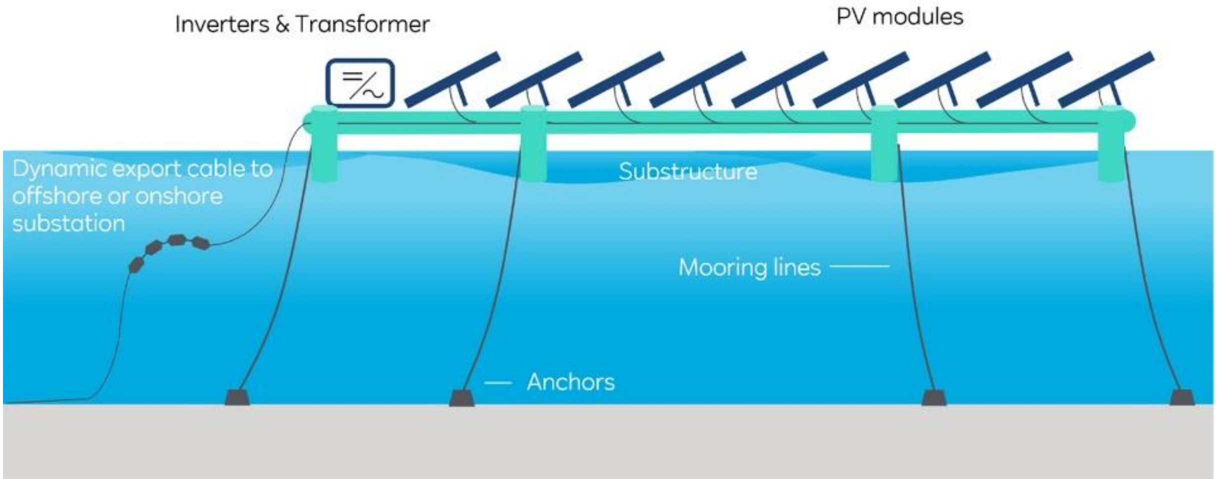

Figure 2: Offshore floating photovoltaics and their anchoring in the sea. Source: RWE Offshore Wind (n.d.).

As Oceans of Energy stated, there are no limitations in water depth when it comes to anchoring and mooring their system (Oceans of Energy, n.d.).

There are two different technologies in structure persuaded by different companies. There is one structure where a platform is built that is high above the sea and the photovoltaic panels on top cannot reach the water surface. This is called “above-the-wave”. The second structure is where the substructure is directly on the water and the panels are in contact with the water. This type of structure is called “on-the-wave”. Both systems certainly have their advantages and disadvantages. Developers and researchers are currently uncertain about which structure is best suited for large-scale implementation. While the “above-the-wave”-structure performs better in resisting erosion due to saltwater and biofouling, the “on-the-wave”-structure is way cheaper because the substructure consists of fewer materials (Jordaens, 2023).

The maturity of technologies is indicated as the technology readiness level (TRL). There are nine levels whereas level nine is the highest and one the lowest (Tzinis, 2012). Offshore renewable energy technologies with TRLs from six to nine are seen as mature (Soukissian et al., 2023). A technology readiness level of five means that the technology is in the phase of laboratory testing of an integrated system. Level six equals “Prototype system verified”. TRL7 means “integrated pilot system demonstrated”. At TRL8, the technology system is complete and qualified. When reaching the highest maturity level of TRL9 the system is proven in an operational environment (Fasterholdt, Lee, Kidholm, Yderstræde, & Pedersen, 2018).

Photovoltaics on land are already mature but to withstand the rough offshore conditions of the (North) Sea there are several adjustments necessary. Firstly, the system must withstand high waves. Furthermore, there are way stronger winds than onshore and depending on the type of technology (on-the-wave or above-the-wave) the wind can strongly reach under the structure. Another important factor is salt. The salt in the water can cause rapid erosion of materials. Therefore, the system must also be adapted to those circumstances (Borriello et al., 2023). Resulting of the various circumstances that make adaptions necessary the technology is not yet ready for implementation. However, on how mature the technology of offshore floating photovoltaics is, there is disagreement in the literature. Also, scientists and producers of the technology give different levels. Nevertheless, consent is, is that the technology is not mature now with TRLs of five to seven, depending on who is asked (Borriello et al., 2023; Soukissian et al., 2023).

In investment planning and to compare different methods of electricity generation, the Levelized Costs of Energy are measured and compared. Levelized cost of energy (=LCOE) is a measure of the average net present cost of electricity generation for a generator over its lifetime. Driving factors for the LCOE are the initial capital costs and the capacity factor, but financing costs, the annual operating expenses and the operational life are important factors (DOE Office of Indian Energy, 2015). For offshore FPV, Oceans of Energy predicts the costs of offshore solar to reach the same cost level as offshore wind (Ocean of Energy, 2019). However, the current reached LCOE by Oceans of Energy is 120 to 150 €/MWh. To compare, onshore PV reaches LCOE under 50 €/MWh and offshore wind farms range from 67 to 140 €/MWh (Borriello et al., 2023).

2.4.1. Spatial Implications

Large sections of space can be dedicated for offshore floating solar and simultaneously no costs are involved with the location (Dana, 2018) in comparison with onshore installations, where the implementation areas need to be purchased. This is particularly important in countries that are densely populated (ibid). Therefore, FPV can serve as a solution for space scarcity.

For onshore implementations, space is often scarce, but that is not the only problem, because where there is space left, there often is resistance from citizens against technologies. This phenomenon is called NIMBY which means “Not in my backyard”. People can be in favour of a technology as long it is far away from them. As soon as they can see it, they oppose the technology. This is a huge problem for onshore implementations and a huge limitation for the energy transition. Offshore floating photovoltaics cannot experience the NIMBY phenomenon and are therefore not that restricted by public resistance (Snieckhus, 2019).

Furthermore, large sections of space can be dedicated to FPV, so that large contiguous areas can be used (Snieckhus, 2019). This is fundamentally different from the structure on land, where only small fragments can be used for energy production and a mosaic of uses exists.

2.5. Conceptual Model

An overview of the used concepts and their relation is provided in Figure 3. It shows that transition theory builds the basis for this thesis. The landscape level consists of the socio-economic, political and cultural context and is for the German case represented by the maritime spatial plan and the energy transition and energy laws. The regime with its dominant rules, norms and institutions is represented by the single-use of space and OWF. The niche with its space for emerging innovations is embodied by the offshore FPV in a multi-use context. The questions this thesis aims to answer is what the potentials and opportunities of multi-use and FPV are to eventually enable the innovation of Offshore FPV in a multi-use setting to thrive from the niche to become a new regime and to support the landscape. Furthermore, it is investigated which barriers act from the landscape and the regime onto the innovation. All together those factors shape the implementation of offshore FPV into OWF in Germany in a multi-use surrounding. The following chapter presents the German case and the methodology used in this thesis to answer the research questions.

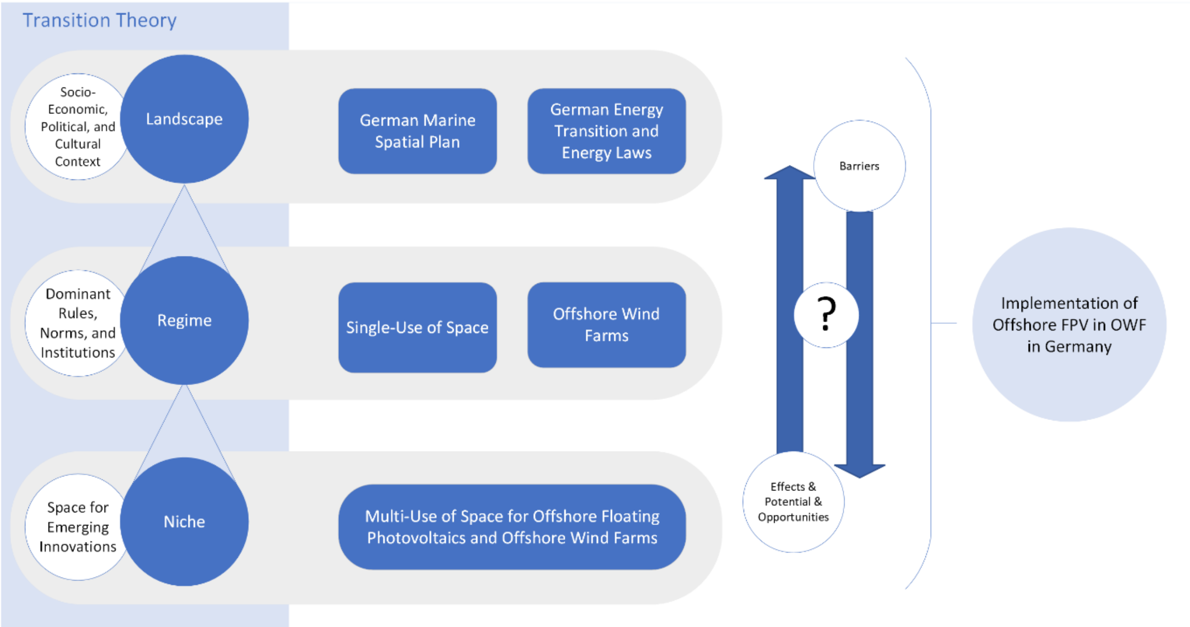

Figure 3: The conceptual model for this thesis. Made by the author.

3. Case Germany

This thesis aims to analyse the spatial potential, opportunities, advantages, and barriers to the implementation of offshore FPV in a multi-use context. It is therefore necessary to introduce in the following chapter the German case with its energy transition, legislation and responsibilities and the current marine spatial plan and the status quo in the EEZ.

3.1. The Energy Transition

As mentioned before, Germany is situated in the middle of its energy transition and its nuclear phase-out with ambitious targets (Federal Ministry for Economic Affairs and Climate Action, n.d.) The core objective of the energy transition is to transform the power sector. As the transition progresses, the significance of low-carbon electricity will grow to ensure a successful transformation (Agora Energiewende, 2022).

The energy transition in Germany is limited due to a dense population, strict spacing rules on land and a strong NIMBY feeling in the population (Borchert & Sutton, 2021; Stede & May, 2019). Therefore, to meet the transition targets, energy production was not only accelerated by installation on land but also shifted offshore, mainly to the North Sea, where wind farms have been and still will be built (Die Bundesregierung, n.d.).

In implementing offshore installation to meet the targets, nature and environmental conservation, as well as the coastal landscape of the North must be taken into consideration. Therefore, in Germany, offshore expansion takes place more than 30 to 40 kilometres from the coast, in water depths of up to 40 meters. This presents special technical challenges, whether it be anchoring the installations in the deep waters using foundations or connecting the renewable energy farms to the mainland power grid (Presse- und Informationsamt der Bundesregierung, 2023).

3.2. Legislation and Responsibilities

In Germany, there are many rules and laws for renewable energies, especially offshore. So far, in the field of offshore renewable energy, there are mainly laws for wind energy.

The construction and operation of offshore wind farms in German waters are subject to several legal regulations. The most important framework conditions are set by the Renewable Energy Sources Act (EEG), the Energy Industry Act (EnWG), the Offshore Installations Ordinance (SeeAnlV) and the Federal Nature Conservation Act (BNatSchG) (Bundesministerium für Wirtschaft und Klimaschutz, 2022). These legal norms form set the cornerstones for the financing of offshore wind energy farms and regulate the connection of offshore wind turbines to the electricity grid. Additionally, they determine the requirements for the approval (and also the implementation) of offshore wind farms (SeeAnlV and BNatSchG) and deal with questions of safety during the construction and operation of the plants (ibid).

The Renewable Energy Sources Act (EEG) was enacted in 2000 and is considered a central factor in the successful expansion of renewable energies in Germany, accounting for over 30 % of electricity consumption by 2016. The EEG's key principle is to oblige grid operators to prioritize purchasing electricity from renewable sources at predetermined feed-in tariffs, making renewable energy investments more reliable and attractive to investors. The feed-in tariffs decrease over time as technology advances and renewable energy penetration increases, encouraging cost reduction and competitiveness. The EEG also regulates the compensation for electricity generated by offshore wind energy installations, determining the tariff rates and duration through regular revisions (Bundesministerium für Wirtschaft und Klimaschutz, 2022).

At the beginning of 2023, the EEG was adapted to consider floating PV on inland lakes and giving the plants a permanent perspective. However, because the ecological effects of the technology on water bodies are still largely unknown as Roß (2022) stated, the EEG only supports systems in artificial or heavily modified water bodies. Plants in natural, ecologically superior waters are still not eligible for subsidies. This restriction is also anchored in the Water Resources Act (WHG). There, it will regulate in the future in a generally binding manner that floating PVs, based on the European Water Framework Directive, may only be erected on artificial waters or waters that have been "significantly physically altered by man". The aim is to allow floating PV only on those waters that have a reduced ecological value due to human intervention. In addition, the distance between the installation and the shore must be at least 40 metres and it may cover a maximum of 15 per cent of the water surface (Roß, 2022).

The Wind Energy at Sea Act (WindSeeG) was introduced as part of the Renewable Energy Sources Act (EEG) in 2017. The WindSeeG governs the support for offshore wind energy installations through competitive bidding processes. It aims to better integrate and streamline spatial planning, site approval, EEG incentives, and grid connection for offshore wind projects, thereby improving cost-effectiveness. The goal of the WindSeeG is to systematically and affordably increase the total installed capacity of offshore wind energy to 15 gigawatts by the year 2030, with steady growth starting from 2021 (Bundesministerium für Wirtschaft und Klimaschutz, 2022). For offshore floating photovoltaics there is currently no such law or regulation. The Wind Energy at Sea Act shows how barriers to the implementation of renewable energies could be overcome and how new technologies could be regulated and promoted.

The Seeanlagenverordnung (=Maritime Facilities Ordinance) is a legal regulation that governs the approval process for sea installations, particularly offshore wind energy facilities and their grid connections. It applies to both the construction and operation of these installations and covers approval requirements, responsibilities, the approval process, and facility monitoring (Bundesministerium für Wirtschaft und Klimaschutz, 2022).

The Bundesnaturschutzgesetz (=Federal Nature Conservation Act) is a law that governs the protection of nature and landscapes. It includes provisions for protected areas and regulates nature conservation outside these areas, encompassing requirements for habitat and species protection. For an offshore wind energy project in the EEZ, the applicant must demonstrate the environmental compatibility of their project to the competent authority, the Federal Maritime and Hydrographic Agency (BSH), as part of the approval process. The project must also be compatible with species and habitat protection. Furthermore, a project developer is obliged to avoid avoidable impacts on nature and landscapes and to explore alternatives. Compensation or replacement measures are also provided (Bundesministerium für Wirtschaft und Klimaschutz, 2022).

The authority in charge of the German EEZ and making the maritime spatial plan is the Federal Maritime and Hydrographic Agency (BSH). The BSH is also responsible for the approval of offshore wind farms and for monitoring the operation of the facilities (Bundesministerium für Wirtschaft und Klimaschutz, 2022). Based on the Offshore Wind Energy Act, the BSH is responsible for the Site Development Plan and thus for planning and investigating sites for the operation and construction of offshore wind energy (The Federal Maritime and Hydrographic Agency, n.d.). Once the site investigation is completed, the Federal Network Agency invites bids for suitable offshore wind energy sites. The bidders receive the results of the initial investigation. Upon successful approval, the winning bidder is granted permission to construct the wind farm on the designated site, receive market premiums, and utilize the capacity on the grid connection (ibid).

3.3. The Maritime Spatial Plan

In Figure 4, the current maritime spatial plan for Germany is displayed. Wind energy, shipping and nature conservation occupy the largest shares of the space of the German EEZ. The maritime spatial plan shows that the whole area of the German EEZ is planned and that there is no “free” space. Therefore, new usages that are not combined with existing ones in the form of multi-use will take space that is currently occupied by other sectors. The only way to keep the current balance between energy, shipping, nature conservation and fishery is to implement multi-use in the German North Sea. In the extension to the Ordinance on the German Spatial Plan for the German EEZ, it is written that due to the long planning and approval periods for offshore wind turbines and offshore connection lines, it is already necessary at the level of the spatial plan to secure areas for offshore wind energy in the long term and to strive for co-use with other uses (Bundesministerium für Justiz, 2021). The co-use is currently not to be found in the maritime spatial plan whereas the annexe Is written for offshore wind farms under the headline “Multi-use” (in 2.2.2., (3)) that insofar as the areas for wind energy EO2-West and EN20 are also designated as reserved areas for research, fisheries research should remain possible in the type and scope in which it is currently carried out (Bundesministerium für Justiz, 2021). At the same time, it says for fisheries (in 2.2.2. (4)) that fishing vessels shall be able to pass through wind farms on their way to their fishing grounds. Passive fishing with fish traps and baskets shall be possible in the safety zones of the wind farms; however, this does not apply to the area bounded by the outer turbines of the wind farm and not to the immediate vicinity of the outer turbines (Bundesministerium für Justiz, 2021). It shows that the only multi-use in the German EEZ the multi-use only occurs with fisheries. This does not meet the definition of multi-use according to Schupp et al. (2019) but is rather to be assessed as co-location.

Furthermore, it is written in the annexe to the Ordinance on the German Spatial Plan for the German EEZ (2021) (in 2.2.2.) that the area development plan (FEP), which is drawn up and updated by the BSH, serves as a technical planning instrument for wind energy. The plan mainly specifies areas and sites for wind turbines, the expected capacity to be installed on the sites and the order in which the sites are to be put out to tender. In addition, the FEP defines routes, route corridors, locations, and planning and technical principles (Bundesministerium für Justiz, 2021).

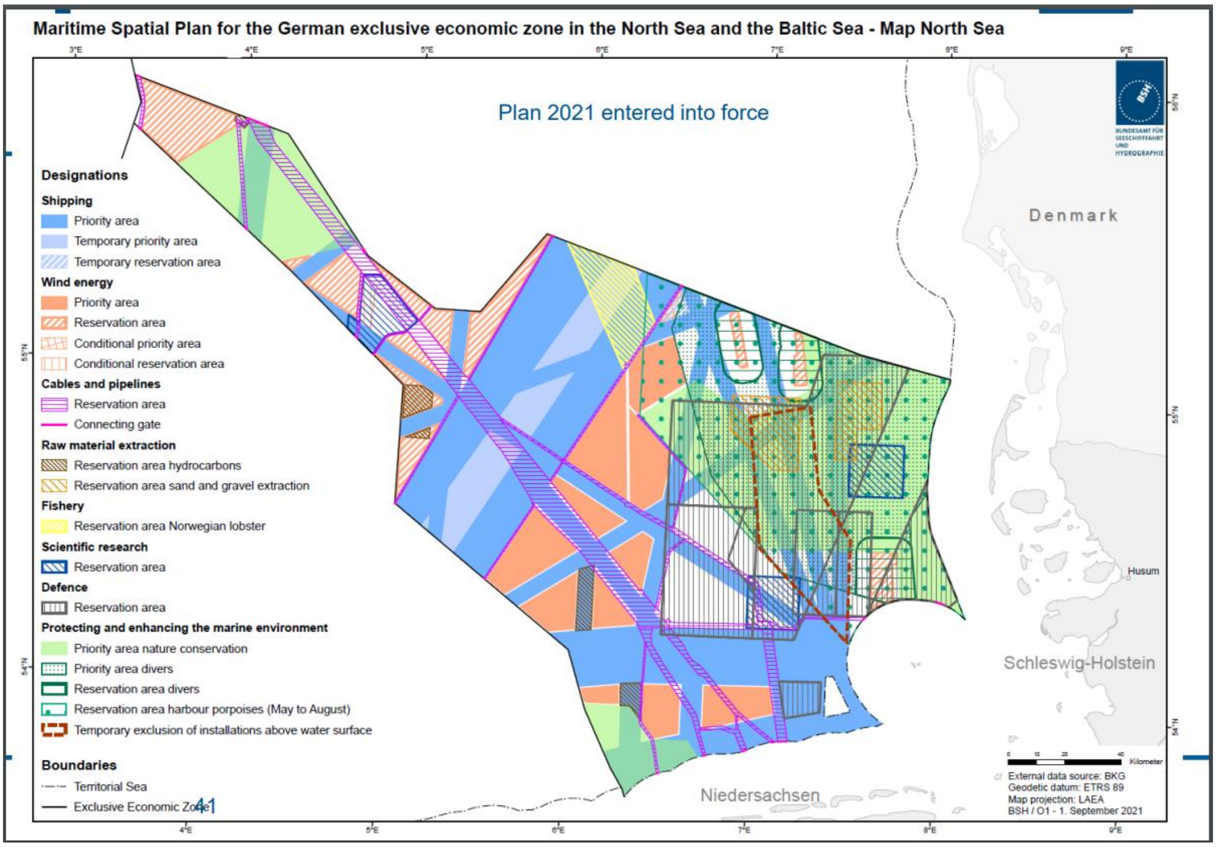

Figure 4: German MSP for the North Sea from 2021. Source: Bundesministerium für Justiz (2021).

An explanation of the different classifications of wind energy areas is that the designation of reserved areas for wind energy serves to secure areas for the further development of offshore wind energy. Similarly, the designation of the reserved areas serves to raise coastal potentials and to secure a further expansion path based on the best possible data, in particular concerning competing uses, subsequently, specific expansion targets are mentioned. The objectives are to be secured by the spatial development plan because they serve the development of the EEZ about a sustainable energy supply for future generations. Due to the lack of conclusive findings on the environmental impact as well as due to the time horizon that goes beyond medium-term planning, the land designations are made as reserved areas (Bundesministerium für Justiz, 2021).

Although already quite a large amount of space is dedicated to wind energy, Nico Nolte, responsible for wind energy planning at the BSH, states that, to reach the German wind energy extension targets, space that is currently dedicated to nature protection must be used (Schröder, 2022). Therefore, it becomes clear that a new technology for energy production, like offshore floating photovoltaics, that share the same space with offshore wind farms, could solve problems that occur due to the competition for space between energy production and nature protection.

Small changes in the spatial arrangement and more details on the spatial arrangement are given in the area development plan, which is published annually. In the 2023 plan, an area of approximately 101.61 km² was declared as an “other energy production area” (Bundesamt für Seeschifffahrt und Hydrographie, 2023).

4. Methodology

The following chapter concerns the methodology used to answer the research questions which are as follows:

Primary research question: *What are the opportunities, what is the spatial potential and what are barriers to the multi-use of marine space and energy infrastructure of the North Sea when integrating floating photovoltaics into offshore wind farms?*

With the sub-questions:

I. *What is the current state of technology for offshore floating photovoltaics and what are its advantages in comparison to onshore installations or other technologies?*
II. *What are the advantages and opportunities of a combination of offshore floating photovoltaics and wind farms in a multi-use context and what is important to consider in planning?*
III. *What are the requirements for implementations in the German EEZ and what is the (spatial) potential of a multi-use of space and energy infrastructure of floating photovoltaics and offshore wind farms in the German North Sea?*
IV. *What are (potential) barriers (in Germany) to implementing floating photovoltaics on the integration into offshore wind farms?*
V. *How could barriers be overcome?*

4.1. Research Strategy and Design

In this chapter, the research strategy and design are elaborated on. Figure 5 displays the research design. This thesis is based on case study research, which will be elaborated on in chapter 4.2. To identify the potential and barriers to as well as analyse the feasibility of a multi-use of space for offshore floating photovoltaics and wind farms in the German North Sea a qualitative research design is used because "qualitative research is oriented towards analyzing concrete cases in their temporal and local particularity and starting from people's expressions and activities in their local context" (Flick, 2009, p. 21). Therefore, a qualitative approach is a suitable tool for answering case study-related questions with the incorporation of local specifics.

For the data collection, a literature review was utilised, a stakeholder analysis was performed, and semi-structured interviews were conducted, for further elaborations see chapter 4.3. The data obtained through the data collection is then analysed and interpreted with the help of an analysis tool, more details on which can be found in chapter 4.4.

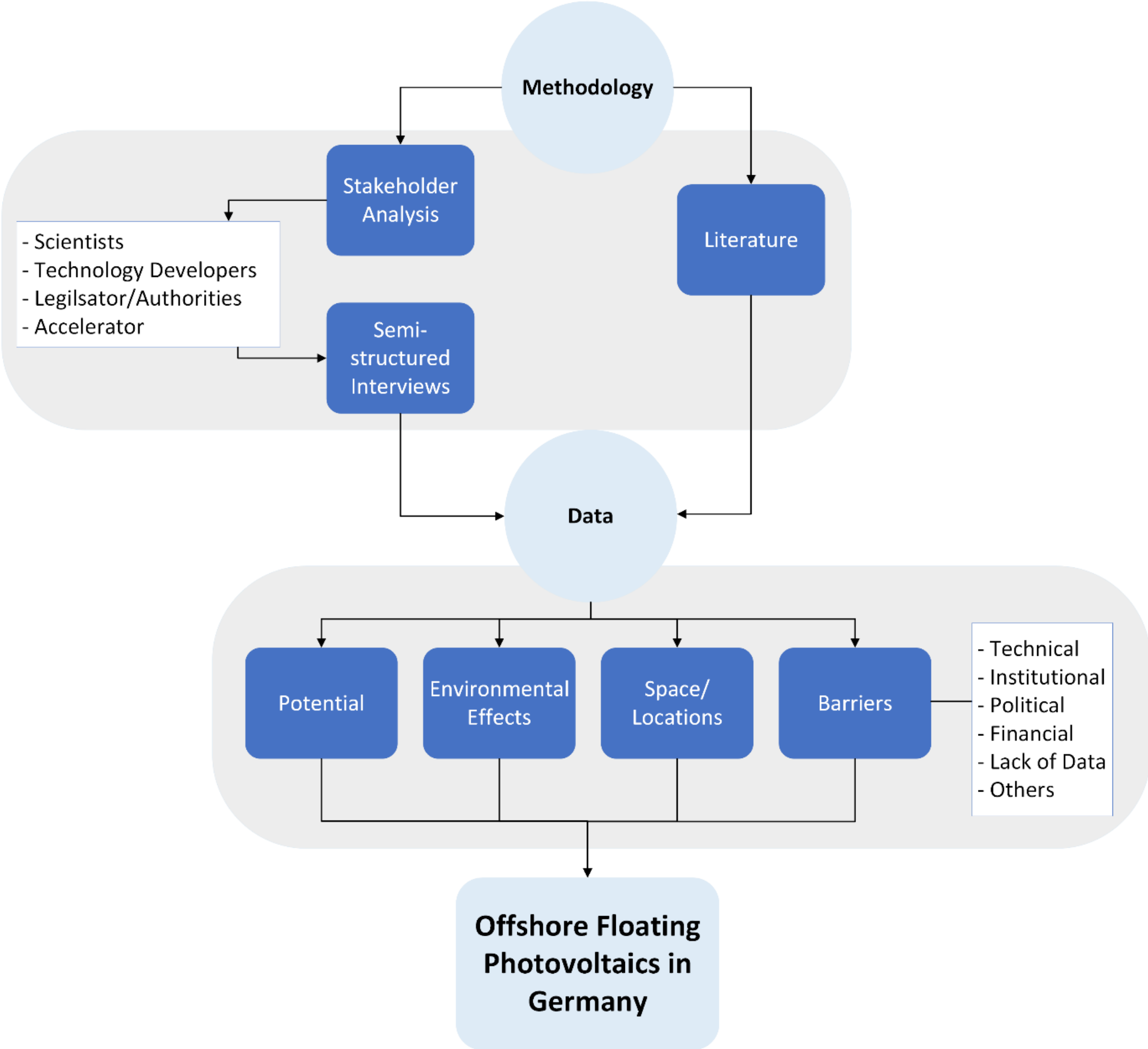

Figure 5: Research design of this thesis. Made by the author.

4.2. Case Study Research

The entity under examination is characterized by its spatial limits, time duration, and theoretical scope (Yin, 2014). Hereby, the spatial limits of this analysis lie in the boundaries of the German EEZ, particularly the German North Sea. The time frame is focused on the state and developments in the year 2023 from April to July. The theoretical scope is determined by the concepts of transition theory, marine spatial planning and multi-use of space which are further elaborated based on literature in chapter 2.

4.3. Research Method and Data Collection Techniques

In the following, the research methods and data collection techniques literature research, stakeholder analysis and semi-structured interviews are introduced.

4.3.1. Literature Research

This study commenced with a literature review. The aim is to evaluate the current state of the development of offshore floating photovoltaics and at the same time to obtain more information about ongoing projects and the case of Germany. In the case of Germany, the institutional conditions, with prevailing laws, plans, practices, and goals were brought together and investigated. For finding first sources, newspaper articles were read that were obtained by searching keywords like “Offshore Floating photovoltaics” in a web search. After finding technology developers and other project members, their websites were examined for further information. For the German case, governmental websites and those of institutions and ministries were scrutinized, for example, the websites of the BSH and the federal agency for justice, where laws, procedures and regulations were found.

4.3.2. Stakeholder Analysis

The identification of relevant actors and sectors is crucial to getting a differentiated picture of the research topic in the end (Brugha, R., & Varvasovszky, Z., 2000). A stakeholder analysis serves as a thorough investigative approach employed to identify and evaluate the significance of specific individuals or organizations that could be of substantial influence over the outcome of a research undertaking (Daniel, 2009). Therefore, a stakeholder analysis was conducted before the invitation of interview partners. Stakeholders were found by searching keywords in a web search like “offshore floating photovoltaics” where websites and newspaper articles were read and analysed. For the German case, the relevant authority for the EEZ and marine spatial planning was researched and classified as relevant stakeholders. Relevant sectors of stakeholders identified were technology developers, accelerators, science and research and responsible authorities.

4.3.3. Semi-Structured Interviews

For an actual overview of the status and the development of offshore floating photovoltaics and multi-use, especially in Germany, semi-structured interviews were conducted. As Adams (2015) formulated in his paper’s abstract: “the semi-structured interview […] employs a blend of closed- and open-ended questions, often accompanied by follow-up why or how questions.”, accordingly, this type of interview is very well suited to understand current developments and institutional arrangements in all their facets and leaves enough freedom to the interviewees to answer the questions from different points of view, depending on the interviewee's background.

The interviewees were invited to an interview via email. The content of the emails was a presentation of the researcher, the topic of the thesis, as well as the research question and the sub-questions. The interviewees were also informed about the reasons to choose them to obtain data.

Before the interviews, a structured interview guide was developed to facilitate organized and informed discussions. The interviewee guide is attached in the appendix. Notably, the guide was tailored individually for each interviewee based on the origin of the participants. The interview guide is organized into distinct sections, including a general introduction, offshore floating photovoltaics, MSP and multi-use and the German case. To conclude, the interviewees were asked about the (perceived) greatest barriers to the implementation of offshore floating photovoltaics in Germany. All questions were asked rather openly to not steer the interviewees in a certain direction.

The interviews were held online either via Google Meet or Microsoft Teams. A total of six interviews were conducted. Further interview partners were requested. However, the requests were declined by some organisations due to time constraints or there were no answers at all. The interviewees came from different sectors as also displayed in Table 1, namely, technology developers (D1 & D2), technology accelerators (A1 & A2), one representative of a science and research organisation (S1) and one participant is part of the most important permitting authority in Germany regarding the EEZ (L1). It is important to note that in interview A1, there were two participants from the same organisation that were later summarised into interviewee A1. The interviews with A2, D1, D2.and S1 were held in English and the interviews with A1 and L1 in German. The interviews were recorded with OBS studio, after getting the permission of each interviewee to record the conversation. After each interview, the interviews were transcribed for further data processing. The interviews held in German were translated into English afterwards.

Table 1: Interview partners with their organisations, sectors and abbreviations used. Made by the author.

Organisation of interviewee	Sector	Abbreviation
Dutch Marine Energy Centre (DMEC)	Accelerator	A1
TNO	Accelerator	A2
Oceans of Energy	Technology Developer	D1
SeaVolt	Technology Developer	D2
Deltares	Science/Research and Knowledge Institute	S1
Bundesamt für Seeschifffahrt und Hydrographie (BSH)/ Federal Maritime and Hydrographic Agency	Licensing/Permitting Authority	L1

4.4. Data Analysis and Interpretation

The data collected during the interviews was coded with the program MAXQDA. The interviews were analysed deductively-inductively. This is the case when categories were determined before coding with the help of the underlying theory and additional categories were created later when statements could not be divided into existing categories (Mayring, 2000; Steinhardt, 2019). The deductive-inductive approach was useful for this study due to the nature of semi-structured interviews and thus answers that were not foreseen before interviews. The resulting categories of the coding are to be seen in the appendix. The codes serve as the basis for the following data presentation in chapter 5.

4.5. Limitations

This study is limited due to the data collection time frame from May to July 2023. Therefore, the specific regulations, states, and developments at that time are part of this thesis and eventual changes that were made later are not included. This thesis is thus a snapshot. Furthermore, there is a limited number of interview capacities due to the time and word limits of this thesis. The nature of the data collection with interviews does not guarantee the completeness of perspectives on the topic of this thesis, as possibly relevant information may not have emerged during data collection. In addition, the results are limited by the fact that there were some connection issues during the interviews, which made it impossible to understand. Furthermore, more interview invitations were sent out than interviews were collected in the end, as some of the people contacted were not ready for an interview or did not respond. This may have distorted the image conveyed by this thesis. Furthermore, the results may be inaccurate by the fact that interviewees may have pursued their interests or may have given false or distorted answers out of a lack of knowledge.

4.6. Ethical Considerations

Before the interviews were held, each participant was sent a data agreement form explaining their rights during the interview and asking for permission to record the interview. Participants were informed that they could refuse to answer at any time and that they could also stop the interview. During the interviews, the questions were asked in such a way that there was no steering by the questioner, but rather open questions were asked so that participants were able to answer the questions freely. To safeguard the identity of the individuals being interviewed, a letter-based coding system was employed to encrypt the participant's names.

5. Results

In the following section, the results will be presented that have been collected from the interviews. The results section follows the structure of the research sub-questions raised in the introduction and in chapter 4. Therefore, this section starts with general data about offshore FPV with the technological demands, challenges, the current state but also the potential, advantages. Secondly, the topic of offshore FPV and OWF is further elaborated on as advantages and opportunities, and the first implications for planning are mentioned. Thirdly, the German case with its planning requirements, procedures and the (spatial) potential for the innovation are presented. Hereafter, the gathered barriers are revealed and lastly, suggestions to overcome barriers, also by learning from other sectors and countries, are presented.

5.1. Offshore Floating Photovoltaics

Offshore floating photovoltaics have currently still technological challenges and there are demands to them that determine the current technical state which is elaborated on in the following. Furthermore, there are advantages in comparison to onshore installations or other technologies that are presented in this chapter.

5.1.1. Technological Challenges, Demands and Current State

Offshore conditions, especially in the North Sea vary a lot from near-shore or even onshore lake conditions. The harsh environment challenges technologies with heavy waves, heavy rains and salty water (D1 & D2). Also, biofouling can have negative effects on the floating structures (D2) and the energetic nature of the North Sea provides additional technical challenges (A1). Technical systems should be adapted to those conditions to ensure durability of a least 25 years to meet the standards for onshore PV (A2). Right now, pilot projects and test sides are relatively close to shore and therefore with different conditions than the real offshore conditions where the system should later be installed. Therefore, there are impacts of wave slamming right now but the height of the wave, currents and the environment will differ later (D2). A test under “real” conditions was thus not delivered and there is still uncertainty about the performance of the technology.

Right now, there are three popular concepts for offshore floating photovoltaics. Some companies produce their PVs that they float on the water, like Oceans of Energy, and companies that follow an “above-the-wave” concept (A2, D2). Both concepts differ in their position to the waves and costs. While the above-the-wave concept provides no necessity to withstand wave slamming due to its elevation, the on-the-wave concept must. Therefore, the panels for the second concept are more expensive. Simultaneously, the first concept's structure is more expensive while the panels are less expensive because the lack of wave slamming makes extra protection redundant (D2). Overall, the on-the-wave concept is less expensive. However, it is not clear yet, which concept is best or if any can withstand the rough conditions of the North Sea for a long time at affordable costs (A2, D2).

The interviewees with direct contact with offshore floating photovoltaics were asked about the maturity of FPV and the answers varied. While one developer from Oceans of Energy stated, that they are now at TRL 7, with demonstrations for over a year, and at the brink of reaching level 8 in early 2025 (D1), the other developer plans to deploy a full test in 2027 (D2). An accelerator stated that floating solar is not yet so far developed as far as the technology readiness level is concerned. That means there are still more hurdles (A1). According to the other accelerator, the TRL would currently be at level 5 (A2). The interviewees are part of several pilot projects, for instance, in the Rotterdam harbour area (A2) and close to Ostend in Belgium (D2). Pilot projects of Oceans of Energy already provide some data and survived some storms with high waves. Therefore, interviewee A2 expresses confidence that the concept is there and able to survive the rough North Sea. The difference in TRL is problematic because it conveys uncertainty about how far the technology is, which creates uncertainty for planners and less incentive to promote the technology. If it was agreed that the technology was already at TRL 7, there would be more reasons for legislators etc. to say that an investment in this technology is worthwhile.

In Europe, no floating solar array is connected to the grid because of regulatory hurdles, for example in the Netherlands, where many pilot projects are undertaken, no electron produced from other sources than wind energy is allowed to contribute to the grid. Therefore, there is still a lot of uncertainty about the grid connection and the performance of floating PV when connected because of regulatory hurdles (A1).

The levelized costs of energy (LCOE) of a technology are important for its success and show whether innovations require subsidies, or similar, to be financially viable. Currently, the LCOE given by one developer with the above-the-wave technology is about 500€ per megawatt hour (D2). The costs of the concept by the other developer are targeted at 250€ per megawatt hour (D2). With those values, the electricity generated by the technology is far more expensive (5-10 times more) than offshore wind energy (D2). Therefore, offshore FPVs are not competitive yet and require several design improvements (D2).

FPVs can only operate at their peak 13 % of the time and then there is no energy generation for a long time, logically the whole night (A1). Therefore, the energy system must not only deal with a fluctuating demand but also be able to balance a fluctuating supply which results from the variability of the sun (A1).

5.1.2. Advantages in Comparison to Onshore Installations or Other Technologies

Implementing floating photovoltaics offshore offers a lot of advantages in comparison to the implementation of other technologies or other areas, for example onshore. The implementation of renewable energies onshore often goes along with the NIMBY phenomenon. This hinders the acceleration of implementation. Offshore, this problem cannot occur, so, there is less resistance against the implementation and therefore the implementation speed is increased

(A1). Additionally, space on land is scarce while the sea offers great spatial potential, so, to meet energy targets, offshore FPV could help.

Another advantage of floating solar is that those plants are less visible from the coast than, for example, offshore wind farms. This means less resistance and simultaneously plants can be installed closer to the shore in areas that haven't been used before (A1).

Another great benefit of FPV is its capacity factor. Especially in the Mediterranean Sea and the whole sun belt, extremely high-capacity factors could offer extremely high yields (A1). In those areas, tourism is very important and therefore the potential for wind energy is limited due to the pollution of the seascape. But floating PV has almost no horizon pollution, thus there is a great potential to open those areas for energy production (A1).

Floating PV is already implemented on a larger scale on inland water bodies, e.g., dams, but none of that can scale (D1). Therefore, a major advantage of floating solar is the scalability. The project size offshore offers great advantages in capacity and while for offshore installations only one project is necessary to reach a certain number of megawatts, onshore, for example on rooftops, many projects would be necessary to produce energy in these quantities. Offshore, the advantages of economies of scale and project efficiency would make offshore solar much cheaper than onshore installations (A1, D1).

Another argument in favour of floating PV is that PVs are more efficient at the same latitude than PV on land because it has constant cooling. The limiting factor for lithium-based solar, which encompasses most of the setups here, is to ensure the cooling of the system because if it gets too warm there is a reduction in efficiency. Due to the temperature, the cooling at the water is constantly ensured, resulting in 10 to 20% more efficiency (A1 & D2). Especially during heat waves, for example during summer in Europe, the efficiency of solar panels decreases because of high temperatures. Offshore installations in those areas would have additional cooling of the water and wind and would perform better (D2). Additionally, the lower operating temperature of PV would be more stable, which might result in benefits for the lifetime of the PV cells in total. Interviewee A2 is more sceptical about the cooling effects and refers to the need for further investigations to confirm that effect.

Another advantage is the efficient use of space and the higher energy density of solar in comparison to wind energy. For example, for the Netherlands, 15% to 20% of the area covered by wind would produce 70 GW but only 1% of the area covered by offshore solar would generate 100 GW (D1).

5.2. Integrating Offshore Floating Photovoltaics with Offshore Wind Farms

Offshore floating photovoltaics can be integrated into offshore wind farms because there are various advantages and opportunities to it compared to a single-use of space. However, there are also difficulties and barriers related to that. Both advantages and difficulties are mentioned in this section. Thereafter, the implications for the planning of multi-used energy farms are mentioned that are collected from the interviews.

5.2.1. Advantages of and Opportunities for a Combination of Offshore Floating Photovoltaics and Offshore Wind Farms

The interviewees with direct knowledge about the technology of offshore floating photovoltaics agree that a combination of offshore FPV and OWF would be beneficial and should therefore be persuaded as there are various advantages to a combination.

The first great advantage to a combination is the cable pooling or the sharing of a grid connection, respectively. Due to a complementary generation profile of solar and wind, better utilization of the grid can be achieved by combining both technologies in one area (A2). This is beneficial because in wind farms the networks are not fully utilized. After all, the wind is not always at peak capacity, but the infrastructure adapted to it (A1). Therefore, cables won't be a problem and in a 700-megawatt wind farm, 300-400 megawatts of floating solar could be added without problems or the need for adaptations (D1). The further offshore an installation is, the greater the cost of bringing the electricity onshore (A1). Concurrently, it is important to use the infrastructure as much as possible because that significantly reduces the cost per kilowatt-hour. Therefore, the sharing of cables offshore allows for cost reductions (A1) and due to previous investments in energy infrastructure for wind energy, the investments in the infrastructure are already made and by an increased grid utilisation there is a cost reduction and lesser necessity to build new cables etc. (D1). Furthermore, the new technology can share costs with offshore wind, which is already more profitable, thus the costs of implementing and connecting offshore solar will be reduced (A1). If offshore solar is to be installed in the North Sea or far from the coast at an affordable cost level, cable pooling and therefore sharing the infrastructure with offshore wind farms is a must, and the capacity factor of the cable is increased (A2). Another advantage of shared cables is that in times with no wind, the energy generated from irradiation can partially fill the gap and contribute to a more constant energy output making the grid more stable (A1 & D1). A further advantage in times of no wind is that floating PV can provide energy to cover the basic consumption of the turbines and thus avoid buying high-prized electricity back from the grid (D2).

A striking advantage is the more effective and efficient use of space, also because wind turbines have increasingly more space between them (L1), space can be used for offshore FPV instead of being empty. This is also desired by stakeholders because some areas are used more intensively but in return, some areas can be freed for other purposes (A1). However, it is important that around the wind turbines, space needs to stay free for maintenance vessels to reach the turbines (L1, D2) but even with that consideration there would be enough space available between four turbines (D2). The more efficient use of space is desirable because the North Sea is one of the busiest seas, therefore the competition for space is high (A1). Multi-use offers the advantage of avoiding competition.

Sharing space can result in higher energy yields per area (A1). This can eventually contribute to reaching the energy transition goals (A2) also because even with the reaching of the target for wind energy with sea cover rates of 20-30 %, there is not enough energy to be energy independent but there is the possibility that floating solar helps to reach that desired energy independence (A2). Annually seen or at the same time, more power can be produced with a combination than with a wind farm alone (A2). After weighing ecological and financial aspects, 10 to 15 % of the area can realistically be occupied with FPV, which will then result in one and a half to two times more energy yield from a wind farm (A1).

A further advantage is the complementary in the supply chain. Therefore, the supply chain ships, the materials and the maintenance of offshore solar are different to offshore wind and won't hamper the expansion of offshore wind energy (A1).

5.2.2. Planning of Multi-Used Offshore Energy Farms

The planning of offshore energy farms is quite challenging and highly complex. Questions arise about whether there should be joint planning of both wind farms and floating solar farms or if floating solar should be added later to existing OWFs. Furthermore, questions arise on how much solar should be added to a wind farm which areas can be used for it and where advantages and disadvantages lie for different implementation options.

When combining floating PV with wind farms, there are electrotechnical difficulties, for example, in determining the optimal connection points for arrays in an offshore wind farm. The solar arrays operate on direct current (DC) and lower voltage, requiring conversion to high voltage alternating current (AC) for integration with existing parks. The question of where to connect these panels arises, with limited options at transformer substations. Due to limited connection possibilities, directly connecting most Floating PV arrays to wind farm substations might not be possible. Hence, intra-arrey cables within the wind farm, involving complex technical modifications, become necessary. These modifications could necessitate temporary wind farm shutdowns, raising regulatory concerns about compensation for revenue loss, costs, and insurance (A1). The primary obstacle is regulatory, even though the technical aspects are achievable but not without associated expenses (A1).

When adding FPV to OWF there are some steps to follow. First, there must be an assessment of the technical feasibility of adding another energy source to your cable because the cables are made for a certain maximum power, which can be when the offshore wind farm is at 100% operation of full wind, which is however not always the case and most of the time the wind is blowing less than the max. which means that there is power available to add on cables. These assessments are ongoing, but dependant on the project, the offshore wind farm, the area, and the cable capacity (A2). So, there is no formula, no ratio, that is the same for every energy park. To answer, how much floating PV can be added to an offshore wind farm depends not solely on the free space in between the wind turbines but also on other aspects. Although an addition of 4-5 times more energy would be possible, financial and ecological aspects included, a maximum of 10 to 15 % of the area in an OWF should be covered by FPV, which then adds up to two times more energy (A1).

In general, the possibility is given, that for every wind farm, floating solar could be added (D1). Recent turbines are built 1 to 1.5 kilometres apart from each other resulting in much space still available to occupy (D2). Limitations arise because the space around wind turbines, within a 100-meter radius, is essential for maintenance vessels to operate. As a result, installing PV panels in this area is not feasible (A1, A2, D2, L1).

When planning an integration of offshore FPV into OWF it is either possible to integrate FPV into existing wind farms or to build them together with different advantages and disadvantages. Some interviewees argue that joint planning would be beneficial, but a later addition is also possible (A1). According to interviewee A1, joint planning is beneficial because then there is only one project developer who builds both technologies into the park that can optimise the business case and the electrotechnical as well as the logistical components (A1). Also, there are some advantages of integrating FPV into the newest wind farms due to electric currents and larger distances between the turbines (A1 & D2).

The integration into existing wind farms is also possible because when the concession for offshore wind is long enough, then the installation of offshore solar can also be added later with many benefits (D1). However, when adding FPVs to wind farms it is important to consider that there should be the same project developer because otherwise, a very complicated regulatory process is necessary (A1).

Planning is always a trade-off between costs and benefits. When planning FPV offshore the trade-off appears in the weighing of location and money because the more offshore the harsher the conditions the higher the costs because the design must be more robust, and the vessels and regulations are more expensive, therefore, there is a trade-off, and nearshore areas that are currently not used should be considered for FPV (D2). Furthermore, it is possible to use not only wind farms that are currently operating for offshore floating photovoltaics but also wind farms that are almost ready for decommissioning because while decommissioning all parts must be removed except for the foundation under a certain height. However, with changes in rules for decommissioning, the existing foundations could be used as anchoring points for offshore floating photovoltaics. With this approach, the operator of the wind farm could save money because he must decommission less and the implementation of offshore FPV is also less expensive because the structure can be cheaper. Of course, this is only a solution for photovoltaics that are mounted to an elevated structure like the above-the-wave concept (D2).

5.3. The Implementation of Offshore Floating Photovoltaics in Germany

To answer the research questions, the German case must be thoroughly analysed, and the planning process understood which happens in chapter 5.5.1.. Subsequently, the spatial potential is drawn from the answers of the interviewees and the areas dedicated to offshore wind farms in the German North Sea.

5.3.1. Spatial Planning and Requirements for Implementations in the German Economic Exclusive Zone

The planning procedure in Germany for the EZZ is quite complex.

When there is the intention to implement floating solar in the German marine space, the process will be as follows (L1). The process starts with an application because, at the BSH, everything is done on application. Only tested and proven technology can be assessed to eventually give a permit and because the authority doesn't test itself, everything must have already been checked before. Environmental compatibility is also of high importance in permitting an application and therefore there must be proof that an installation is not harmful to the marine environment and other protected assets and has as few negative effects as possible on other users and uses and the marine environment. The better the knowledge there, the easier the judgement. Additionally, political backing, economic expertise and the necessary money must be there beforehand (L1). Also, the grid agency and everyone with a stake are important as well as the knowledge that the product can last long enough in the harsh conditions (L1).

Overall, if big companies already have wind farms in an area and when there is a concept for interactions, an application should be easier (L1). When someone has the intention to implement offshore floating photovoltaics in Germany, in general, the interviewee from the BSH said, that the current spatial plan would allow multi-use (L1).

Every offshore energy installation needs to be connected to the grid as soon as a (wind) farm is completed to directly start operating (L1). In Germany, the grid connection is being done step-by-step. The federal states must carry out a regional planning procedure to be able to implement the corridors, including new corridors for several connection lines from the EEZ to the land via and through the islands to the mainland which is often a controversial topic. Overall, that process takes a long time and is highly bureaucratic (L1).

During the interview, it was suggested to integrate the innovation into wind farm tenders, and it was answered that areas are defined by the BSH, and a suitability test is then carried out either by the BSH itself or after the area has been given away. Therefore, the procedure would have to change to make specifications in the tenders. However, the internal discussions would show that the authority is not yet ready to make regulations, especially regarding multi-use (L1).

5.3.2. The Spatial Potential for Offshore Floating Photovoltaics in Germany

Germany has a great spatial potential for offshore floating photovoltaics, especially when combined with offshore wind farms. In countries with already a large offshore wind sector, such as Germany or the Netherlands, with many wind search areas, and already existing wind farms the biggest opportunity is that there is no full utilization of the state-financed electricity network and floating solar could use that and increase the efficiency (A1). Furthermore, the implementation of solar panels offshore could help with land scarcity and avoid stakeholder conflicts (A1). Germany is a country with not that much space at the sea, therefore the addition of floating solar would be beneficial (D1). Furthermore, there is ample space between wind turbines (D2).

In Figure 6, the German North Sea with the areas designated for wind by the maritime spatial plan is displayed. It shows that there are many areas already used for wind farms (priority areas) but also that there are many areas only reserved for wind farms and therefore with no implementation of wind farms yet. Based on the earlier results, it becomes obvious that both, existing and newly planned windfarms, are suitable for FPV installations, but that joint planning would be easier. The figure shows the great spatial potential when allowing a combination of both technologies in a "real" multi-use in the German North Sea because a great share of the German EEZ is dedicated to offshore wind. Accordingly, a lot of space can also be used for offshore FPV.

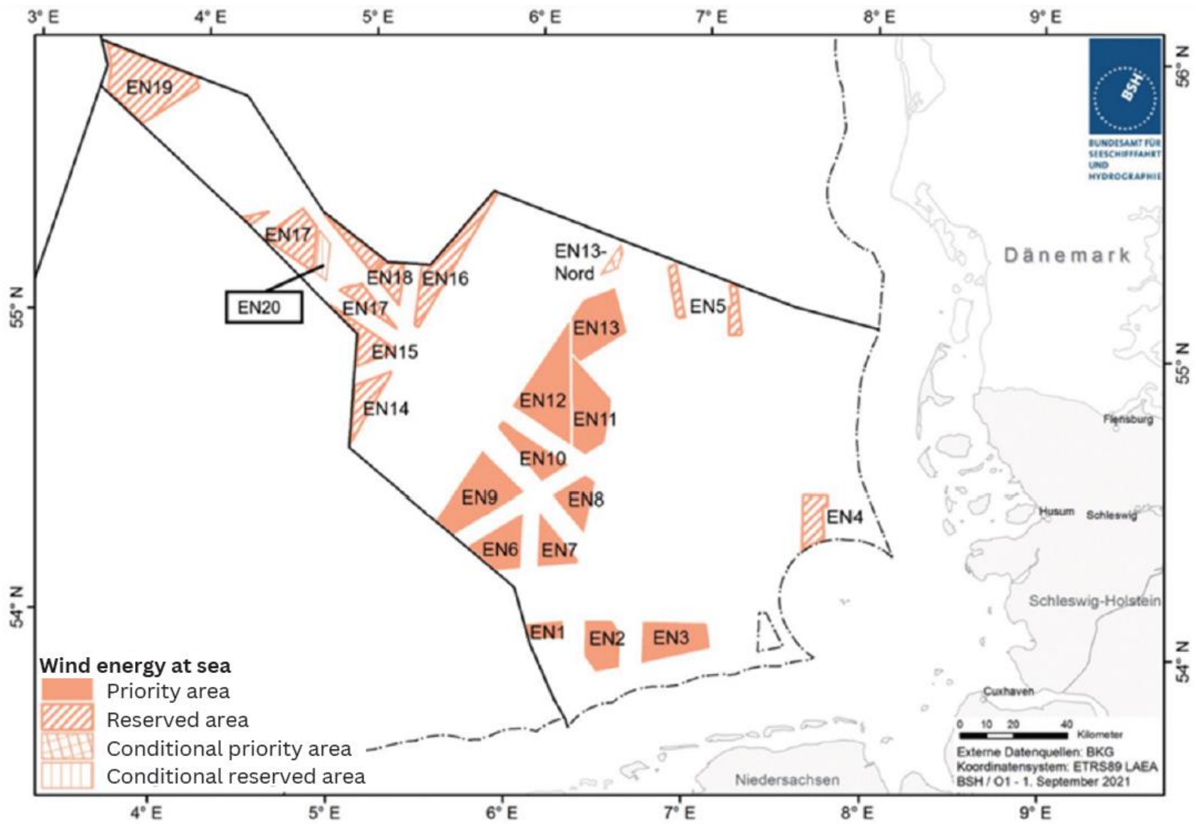

Figure 6: The German North Sea with the areas designated for wind by the maritime spatial plan. Source: Bundesministerium für Justiz (2021).

Besides the marine spatial plan, there is the land development plan which is a more detailed area plan for the German EEZ and is released annually. In the recent land development plan, areas were not only tendered for wind energy but also for other energy production. These areas are mainly used to produce hydrogen but are not specifically reserved for this purpose and are put to tender separately (L1). Therefore, there is an opportunity to apply for offshore solar to be installed there. However, the area is currently very small and despite the possibility of putting more other energy areas to tender, it will, the estimation of L1, take a few years until the right conditions are, also there because of promotion and support from the political side are decisive and currently primarily there for hydrogen (L1).

5.4. (Potential) Barriers to an Implementation in Germany

The implementation of offshore FPV is very dependent on the right circumstances. As mentioned before, there must be a window of opportunity, but there are also barriers which are important to address to facilitate the transition, as Geels (2014) highlights. Accordingly, this section aims at the identification of barriers that potentially arise to eventually provide the basic assumptions to overcome them. This chapter is subdivided into different forms of barriers, namely barriers arising from environmental effects, institutional, financial, and political barriers, barriers related to the lack of data or other barriers that cannot be categorized.

5.4.1. Environmental Effects and Barriers

During the interviews, it became evident that there are challenges in handling and planning multi-use, renewable energies and technological innovations while simultaneously considering the environmental and the effects of implementations. The result is uncertainty about how to plan and prioritize different related topics. For instance, the weighing between dedicating space for energy and ecology poses a challenge due to tensions between water quality and the energy transition (S1). Further tension arises between environmental concerns and economic viability because floating solar farms should be economically viable but also eco-positive with good light penetration to avoid harm to water life (A2). It becomes thus clear that the implementation of the innovation in the marine space should not be done without knowing the environmental effects thoroughly, also to better consider how much space can be occupied by the new technology. Furthermore, as stated before, knowing the environmental effects of technologies is very important to mitigate them and for getting permits. The problem with offshore floating photovoltaics is, that it is a relatively new technology to deploy offshore and therefore there are not that many known effects on the marine environment. Consequently, environmental effects might serve as barriers but not-knowing them might as well.

There might be positive effects on the environment. For example, there is the hypothesis, that in very hot summers that will increase due to climate change, floating PV can offer cooler water of refuge for fish and can also prevent evaporation (S1). These positive effects might be actual for lakes or similar onshore conditions, but it's not clear whether it's also true for marine environments, because there is hardly anything installed yet (A2).

Offshore floating photovoltaics cover the water's surface. Therefore, there is a reduced light penetration of the water. This might result in lower primary production because algae are less active (S1). However, whether there is a reduced primary production is not certain yet and needs to be investigated further (S1).

Structures in the water attract the growth of algae and mussels on it. Whether that is positive or negative cannot be assessed conclusively. Some say that the creation of new habitats is positive, but others say that the North Sea is naturally sandy and empty and therefore new habitats don't belong there because they are not natural (S1). Others say that they experienced reef-building and interpret this as a positive interaction between the PV panels and the sea (A1 & D1). While biodiversity might increase with those new habitats, the chances for invasive species will increase as well (S1).

The interviewee from science was also asked whether the mooring will also cause any environmental problems but because of the sandy nature of the North Sea, the mooring won't cause an environmental problem because there is not much to destroy (S1).

(Floating) structures in the marine environment will attract birds that will sit on it (S1, A2). Those birds will provide bird droppings that could have negative effects on performance and corrosion, especially in periods of dryness, where rain cannot wash any dirt away (A2). Birds are very difficult to distract (S1). When considering the implementation of FPV in OWF there are additional problems. Attracted birds might be harmed by the wind turbines. Consequently, the rate of victims will increase (S1). Subsequently, there are effects of a multi-use of space that only arise when technologies are combined but not when they are installed alone. Hence, a study must be done before to assess the cumulative effects.

Not only birds are attracted by floating islands, but also other animals. One interviewee (A2) reported from seals that rested on the panels in a pilot project which could of course damage the panels but also negatively affect the animals.

To connect floating photovoltaics to the grid, cables are needed. Those cables create an electromagnetic field that might impact fish, especially deeper living ones (S1).

Solar panels are made of artificial materials. Therefore, with scratches, moves against each other or erosion, microplastic might be released into the marine environment (S1). Additionally, there is the possibility of the diffusion of chemical substances into the water from the panels, which might have negative effects on the water quality or the ecology (S1).

Whether the ecological effects will be significant or neglectable is not determined yet. Due to the low area occupancy, some say that for the whole area of the sea, the effects should be negligible and only local effects are to be expected (A2). Furthermore, currents in the water result in a dilution of effects on e.g., oxygen (A2), because the water is still able to flow beneath the structures (D1). However, an upscaling could result in effects that were previously neglectable (A2). Accordingly, for the planning process, interviewee S1 highlights the importance of considering the environment and the cumulative effects of the multi-use of space for offshore renewable energy and that she would prefer an environmental assessment before joint planning of both technologies to prevent enormous loss of production in the North Sea (S1).

5.4.2. Institutional Barriers

Occurred institutional barriers for the German case are especially the prevailing laws for the EEZ and renewable energy generation, but also the procedures within the licensing authority BSH along with general institutional and non-place-specific barriers mentioned in the interviews.

Institutional barriers that occur not only in Germany but also in other countries are due to a lack of regulation for new technologies and certain rights of use (A1). Regulatory uncertainty arises due to potential curtailments when there is more energy generated than the grid's capacity allows for, what is prioritized and who pays for it. Questions of curtailment and shutdown of plants are especially important when there is more than one owner in an energy farm with at least two technologies (A1).

Additionally, there are other questions to answer by regulations yet to come, for example regarding retrofitting an offshore wind farm with floating solar: "Who pays the revenues for shutting down the area that must be shut down? Who pays the costs, and who pays the insurance if there is damage due to these changes within the wind turbines? Because all this basically belongs to a project developer, not to the state" (A1).

The occurrence of institutional barriers could delay the implementation of floating photovoltaics significantly. Nevertheless, some important steps need to be taken as quickly as possible to still have effects before 2030-2035 because five to ten years before that the regulators need to start working on these so that it is possible to include them (A1).

As of right now, there is no mention of offshore FPV at all in German regulations. Only for onshore floating photovoltaics, there are regulations since January 2023. This makes implementation in Germany difficult and therefore it is not surprising that interviewee A2 said: "I really am not aware of any initiatives in Germany" and Interviewee D1 said: "I think Germany is quite interesting for offshore solar and I think that it should be addressed better by the German authorities".

The interviewee from BSH revealed that without specific knowledge and findings regarding a technology, an implementation is not possible. Consequently, there is no consideration of that new technology in upcoming tenders (L1). Also, there is a lack of innovativeness as the BSH is limited to its part of the business and won't look further into what might be important in the upcoming years (L1). Therefore, the German authorities rely on other countries, like the

Netherlands, to test new technologies. If they turn out to be good, then Germany will adopt them. But until then, she said, the authority pursues a wait-and-see approach, also because the decision-making paths are not as short as in the Netherlands, they would be more bureaucratic and would have to cover all the risks before, after then, the legal arrangements could be made (L1).

For offshore floating photovoltaics there are other supply ships than for offshore wind farms. While one could argue that this is to evaluate positively because then the new technology won't hamper OWF (A1), that might also work as an institutional barrier because every ship that enters a park has to be certified beforehand to enter and move within the OWF, also the captain must have certain qualifications (L1). Difficulties can also arise in the logistics, for example, the questions when it comes to maintenance etcetera. "When can which ship enter the park? Who has priority? This is also a difficulty because one of the biggest restrictions is weather windows" (A1). Furthermore, an operator must always monitor and observe the sea and who comes in and out of his energy park. Additionally, the operator is responsible for the existence and monitoring of pipelines, which in sum creates an obstacle to the efficient and economical generation of energy by an operator. Therefore, a large-scale implementation could be delayed and limited by bureaucratic mechanisms that serve as institutional barriers.

Another institutional barrier in the form of procedures in the agency is that the agency BSH cannot test itself. Therefore, the technology must be very mature for an application to be successful and thus the industry must test itself or the testing must happen in other countries (L1).

5.4.3. Financial Barriers

Financial barriers arise due to the necessity to build financially feasible plants despite having immature technology with technical challenges yet to be solved and the lack of proof of financial viability (A1 & D2). Financial viability means in this context financial cost reduction (A1). The still very high levelized costs of energy are limiting the financial viability of FPV and create a risk for investing in the technology that hinders investors. (A2 & D2). Further, the costs that result from connecting the floating solar farms to a grid connection point are also limiting factors (A2). Financial cost reductions must come from scaling (A1) which requires certain technological maturity. To reach TRL 8 from TRL 6, a lot of money would be required (A2). Also, funding could lead to scaling (D2). To up-scale small systems to a commercial alternative with the opportunity of integrating them, enormous investment rounds would be necessary with high amounts of capex and pre-investments. Without funding, developers would never invest in a full-scale demonstration (D2). This shows that funding helps developers to increase their technological maturity and to start full-scale demonstrations, consequently, the absence of funding leads to stagnation. However, there is a funding gap (D2). Also, scaling requires sufficient regulations (A2).

5.4.4. Political Barriers

New technology won't be self-supporting from the start. Start-up and research funding is thus imperative (L1). However, in Germany, various ministries are involved in funding and therefore it becomes a political topic that strongly depends on the elected parties and their attitude towards innovation and thus their willingness to promote the innovation (L1).

That political backing is crucial for the implementation of new technologies is confirmed by multiple interviewees. For example, in May 2023 the Netherlands established a target of installing 3 GW offshore floating photovoltaics by 2030 (A1, D1). The targets lifted a huge barrier because they gave developers security (D1). With targets, developers could argue, to get funding, and there is a political will, which would be very important, especially because the concept could not yet be demonstrated (A1). Political targets for technology could help with lifting financial barriers. With ambitious targets, a market size would emerge with big companies, big investors, big insurers, etc., that would collaborate towards a common aim (D1).

For the German case, the interviewee from the permitting authority stated that without political backing and economic expertise, a successful application would be very difficult (L1). She said that promotion and support from the political side, the grid agency and everyone with a say would be inevitable. Interviewee A1 also confirmed this "Of course, government support is needed, as was the case with wind back then" (A1). However, the political backing could be hampered due to the current development of hydrogen in Germany because it would be the first thing on the agenda and they would have to see how that works, also offshore, before dedicating themselves to another topic(L1). Interviewee L1 is not seeing governmental agencies making attempts before to see, where to possibly implement offshore floating solar. Afterwards, she said, there would be the opportunity to define areas in the land development plan for floating solar to give operators the chance to implement the combination of OWF and FPV in a multi-use context and to try it out (L1).

5.4.5. Barriers Resulting from the Lack of Data

The lack of data can be a huge barrier to the implementation of a new technology.

In Germany, there is currently no "real" multi-use, but there is a study commissioned by the UBA (Federal Environment Agency) that investigates the potential for multi-use in the German EEZ that is not finished yet (L1). In addition to technical aspects, it is also about additional spatial potential for offshore wind energy "We are looking at […] whether we can combine this with other forms of energy production, and one suggestion was photovoltaics." (L1). In addition to that, there is a study put to tender by the BSH, where the topic of multi-use is being investigated in all conceivable constellations, not just energy. However, the results will be accessible as early as the beginning of 2025. Right now, "this is […] a very new topic and there is simply too little knowledge about it" (L1). The results of the study will provide insights into the necessary specifications determined by the land development plan and which requirements can be placed on applicants. Without that kind of knowledge, it would be difficult for the authority to deal with applications. The lack of data is thus a huge barrier. This is not only the case for the lack of knowledge in institutions on how to deal with multi-use, but also emerging due to the unknown environmental effects. Especially in Germany, where the knowledge about a technology and its handling determines the success of an application (L1). As interviewee L1 articulated, a permit can only be granted when there is relevant knowledge. She expressed that there is still too little knowledge about the multi-use of space but also the behaviour of the floating structures in the marine environment and especially questions about the cables and their connections are rather open and pose new challenges to the authority (L1).

The lack of data expresses itself also in the lack of a proof of concept because, in the Netherlands, where many projects are ongoing, no grid connection was possible (A1). Furthermore, offshore floating photovoltaics are only tested in test sites near shore that don't meet the real offshore conditions. Therefore, it is not certain yet, whether the technology will withstand the harsh conditions it is made for.

There are other problems where the lack of data is the reason. Questions like "How much space can you commit to energy and how much space is left for ecology and is that enough?" (S1) are not answered yet and the scaling might result in ecological problems. "What if we scale up twice or three times or four times and then there will be a point where things will change" (S1). Interviewee A2 confirmed this and said that they don't know the exact effects on the environment yet because there is no large-scale demonstration. Interviewee S1 also explained that in Asia there already are many floating solar farms implemented on reservoirs and estuaries, but there are great difficulties in getting data from them, although they measure the ecological impacts.

Right now, there is no knowledge about which of the concepts on-the-wave or above-the-wave will perform better. This kind of uncertainty results in a barrier because companies pursuing the more expensive structure will have to discontinue their project if the cheaper approach proves suitable for ocean conditions (D2). However, currently, several companies are trying to get subsidy projects to investigate their specific concepts and to see whether this concept is suitable for the typical circumstances on the North Sea and "There is no winner yet" (A2). Therefore, a lot of money needs to be invested with the possibility that a big share of it is wasted when a concept proves to be less viable.

5.4.6. Further Barriers

There are further barriers that emerged during the interviews that were not thought of beforehand and did not occur during the theoretical research. Therefore, those are mentioned in this section. Further barriers to the implementation of offshore FPV are for example the need for skilled workers or space in harbours (A1). L1 depicted the German case that there are too few people who build and maintain wind turbines because there is just as much of a shortage of skilled workers as in other sectors in Germany.

Right now, there are many financial risks associated with building offshore wind farms (S1, L1). This risk also serves as a barrier because “this risk is something that we as a company […] don't want to take”. As long as there is no funding, the risk is therefore too high for developers to install more projects.

The operational experience is another barrier to implementation. Currently, there is no proof that the system can withstand 25 years (D1). However, as the interviewee from the permitting authority stated, it is very important to know that a system would live long enough to give permits for its implementation (L1).

Another barrier is that there is limited availability of testing infrastructure. One developer said that it is difficult to find an area where it would be possible to integrate offshore solar into the grid (D1). Without proper testing, the technological readiness level cannot increase towards commercial readiness.

In Germany, the grid is sometimes already overloaded with the electricity generated by wind farms because the expansion of the grid connection progresses not as quickly as it should, therefore sometimes plants still have to be shut down when there is too much wind which cannot be transported (L1). Accordingly, the question arises whether the problem will increase when adding floating solar to the grid or if this is neglectable due to the anti-correlation of wind and solar.

5.5. Overcoming Barriers

To overcome the barriers to the implementation of floating photovoltaics, also in a multi-use surrounding with OWF, especially in Germany, there are a few suggestions made by the interviewees that are presented in the following section. Furthermore, there were some experiences shared from other sectors and countries that allow for learning from Germany to facilitate the implementation of offshore floating photovoltaics. This section corresponds with the last research question: *How could barriers be overcome?*

5.5.1. Learning from Other Sectors

The expansion of offshore floating photovoltaics could benefit from the experiences made during the expansion of offshore wind energy because wind energy is in a state of flux and the know-how is already there (L1). Also, with offshore wind, Europe is quite good in terms of industrial leadership for wind turbines as well as in the installations of projects and their financing. Therefore, there are lots of lessons learned from the offshore wind industry that can be applied to offshore solar (D1). It appears that especially regarding the financing mechanisms learning from offshore wind energy is possible.

In Germany, when there is political will, things can progress quickly because political pressure and lobbying of the respective industry make a difference (L1). For example, the wind industry would be very successful with lobbying and current hydrogen developments with area and funding allocation and new programmes and pilot projects would be attributable to this. Therefore, the floating solar industry can learn from wind energy and the current development of hydrogen (L1). It shows that the lobby work by the other sectors is very successful, and companies should thus try to do the same for offshore solar energy. Interviewee A1 also stated that governmental support is needed to get a cost reduction that comes from scaling “as was the case with the wind back then” (A1) and Interviewee A2 said that feed-in-tariffs, that were used for offshore wind, could also help to give security when implementing offshore FPV. It becomes clear that political will and financing mechanisms are essential assets for innovations to spread, as wind energy development has shown.

For onshore solar development, Europe lost its technological advantages in the early 2000s to China (D1). Therefore, there can also be learning from that to avoid losing a leadership role again.

5.5.2. Learning from Other Countries

Other countries are further in their development regarding the implementation of offshore floating photovoltaics and multi-use than Germany. Consequently, there is the possibility of learning from those countries.

For example, there is the Dutch 3 GW target of floating solar to be installed by 2030 while there is no movement yet in Germany (A1 & A2). This Dutch target would be large enough to convince organisations and the industry to start making sure that the implementation is possible and start scaling the technology (D1) which further accelerates the development of the technology. Furthermore, the target creates pressure from the markets for the developers which will accelerate and motivate start-ups or scale-ups to develop on a higher base to achieve these targets (D2).

Moreover, Germany could learn from other countries regarding their handling of multi-use because although there is no basis for multi-use in Germany yet, neither in the current tender planning nor in the sub-station planning, it is coming in the Netherlands and Belgium now (A1). Additionally, the topic has already arrived in politics there and multi-use, particularly the integration of other renewables, is addressed by the marine spatial plan (A1). Therefore, Germany is lacking behind its neighbour countries and can learn from them (A1). In the Netherlands, the tendering now makes it possible to mandate the integration of floating solar into the bid offers: “The offshore wind park operator could earn points with the tender by integrating or including an offshore solar system […] And so if the offshore wind company just includes offshore solar as an integral part of the wind park, then they can earn points and in the end, it's the bidder or the tender with the most points that will win the bids” (A2). This approach promotes innovation.

Regarding the availability of testing sites, there are also a few differences between Germany and other countries. In Belgium there are testing sites owned and provided by the government (D2) as well as there is the availability of testing sites in the Netherlands (A2 & D1). Furthermore, there is a bit of funding in the Netherlands (A1) and in Belgium (D2). The mechanisms used in both countries could thus serve as a role model for German development.

Some things can be learned that serve as barriers in other countries that could be investigated for the German case before implementation to be ready for the technology when it is mature. For example, there is no grid connection possible in the Netherlands for FPV due to restrictive regulations (A1). So, for the German case, one could investigate whether there are similarities in legislation.

5.5.3. Suggestions to Overcome Barriers

The interviewees not only stated which problems occurred in their work but also suggested measures to overcome those problems and barriers. The suggestions made are articulated in this section.

Changing regulations by integrating offshore floating photovoltaics as a criterion in wind farm tenders would help implement offshore floating photovoltaics (A1, A2) and would be the most important step because then sub-stations are adjusted. Then the project developer adjusts and will still develop the wind farm because there are enough requests and simultaneously, floating solar cells are built subsidy-free. The more is built, the cheaper it becomes (A1). These changes in regulations would be the first important steps that need to be taken as quickly as possible to have an effect before 2030-2035 because 5 to 10 years before that, regulators need to start working on these topics so that it is possible to include them (A1). The second step would then be to set certain targets for certain gigawatts by a certain year, which is also done with offshore wind and as the Netherlands has done for offshore solar. Then, subsidies should follow, and annual contracts-for-difference or feed-in tariffs should be provided and incentivised for wind farm operators to integrate offshore solar at their sites because offshore wind farm sites would have more than enough available electrical transmission capacity for integrating offshore solar (D1). However, integrating it would pose a possible challenge to existing contracts and required arrangements may result in costs for the offshore wind farm developers. Currently, no mechanism incentivises offshore wind developers to make those investments, therefore, incentives are required. However, there is not necessarily a need for subsidies if offshore FPV is included as a criterion for offshore wind tenders, thereby indirect subsidies via the infrastructure would occur (A1).

Important is that floating solar cells should be able to feed into the grid to a certain extent, which needs to be investigated prior (A1).

Of course, an adjustment of German laws and regulations is also inevitable. Interviewee L1 proposed to integrate offshore FPV into the Wind Energy at Sea Act because many things would then be similar again and additional requirements could be integrated. Another possibility is to include it in the EEG.

To prevent environmental harm, there should be an assessment that examines the cumulative effects of technologies in multi-use surroundings (S1). It is suggested that the authorities when giving a permit, include and demand a monitoring plan with monthly measures of temperature, oxygen, light penetration, and plankton, particularly phytoplankton, but also fish and birds (S1). For birds, it was additionally proposed, to stop windmills when there are a lot of migrating birds there for a day to prevent harm to them (S1).

To avoid conflicts with current uses such as fishing in Germany, which uses wind areas, an early exchange with fishermen was proposed (A1).

Interviewee A1 suggested creating more offshore demand for energy to avoid laying new cables, for example, with the production of green hydrogen directly at the offshore energy farm. In addition, it would be beneficial to integrate energy storage or electrolysis (D1). Also, the storage could be used more efficiently when implementing solar into a wind farm that charges the storage because, with higher utilization, it becomes cheaper. Currently, the capacity factors and utilization rates of electrolysers lie at 50 % which could be increased with offshore solar and thus the price of hydrogen will decrease (D1).

6. Discussion and Conclusion

In this chapter, the results of this thesis are discussed, and a conclusion is drawn. Throughout the chapter, the sub-questions raised in the introduction and the methodology are answered.

6.1. The State of Technology

The results indicate that the technology of offshore floating photovoltaics is not mature yet but is on its way towards maturity. Several projects in countries like the Netherlands or Belgium contribute to further development. Currently, the levelized costs of energy are too high to create a viable business case with the technology. Also, there is a lack of experience in the longevity of the modules in the rough conditions of the North Sea. These technological values make the technology not yet competitive with other renewable energies like OWF. Despite that, the technology offers various advantages to other technologies or locations such as the avoidance of the Nimby phenomena, lower visibility, high capacity factors, its scalability, a cooling effect from the water that results in a higher efficiency and a higher energy density than offshore wind farms.

6.2. Advantages and Opportunities of Combining Offshore Floating Photovoltaics and Wind Farms and Implications for Planning Practice

A multi-use of space with offshore wind farms creates a variety of advantages, such as a sharing of infrastructure like cables and substations. In addition, space can be used much more effectively and efficiently and the energy density per area can be increased significantly.

The planning of offshore energy farms, however, is challenging and highly complex. Questions arise about whether there should be joint planning of both wind farms and floating solar farms or if floating solar should be added later into the existing OWF. There are a few advantages and disadvantages for both cases that should be considered by planners when planning to implement offshore floating photovoltaics.

On the one hand, there are a few advantages when implementing new offshore FPV farms into existing OWF. For example, there is an increased energy capacity of the energy farms and a balancing of the energy output. Furthermore, the older wind farms are usually closer to shore, which facilitates the implementation and reduces the costs due to gentler conditions closer to shore and the harsher the conditions, the higher the costs of offshore FPV.

On the other hand, there are also disadvantages of a later implementation of FPV because the energy conversion from direct currents (DC) to alternating currents (AC) is necessary. Therefore, there are more investments to be made and the implementation is more complex. Furthermore, the questions about the shutdown of offshore wind farms are not answered yet and it is therefore not clear how to deal with the shutdown of plants for the connection. Also, there might be a difficult regulatory process, if the developer of both, solar and wind farms, is not the same. For the German case, there are additional elements to consider, currently, the space of the North Sea that is dedicated to offshore wind farms also allows fishermen to pass through and fish. When integrating offshore FPV into wind farms it is thus a conflict potential arises. To solve this, an early dialogue with fishermen is inevitable to avoid further conflicts and delays in the implementation.

The advantage of joint planning is that new plants work under direct currents, thus the energy conversion is redundant. Additionally, there is the opportunity to adapt and plan sub-stations with more connection points, allowing for direct connections without modifications of the sub-stations. Furthermore, the questions about the developer are then solved. Either it is only one developer, or two developers have contracts that clarify questions about finances and curtailment etcetera. Another advantage of joint planning is that new rotor blades of wind turbines are much bigger than they used to and therefore there is more space in-between wind turbines. Consequently, there is more space for eventual offshore FPV. Finally, an advantage of joint planning is the opportunity to mandate the integration of FPV into new wind tenders which will accelerate the implementation of the new technology automatically.

A disadvantage of joint planning results from the advantages of a later implementation into existing wind farms – the new plants are usually farther from the shore and therefore the conditions that the systems must withstand are harsher. Consequently, more money is needed for technology adaptations.

In the end, it must be decided individually for each implementation whether integration into existing wind parks or a joint planning process is more advisable. It certainly is evident that both cases have some advantages and disadvantages. While joint planning does not require any turbines to be shut down during construction and probably only one operator is responsible, implementation is facilitated. At the same time, old wind farms are usually closer to the coast and thus adjustments are less necessary, and construction is cheaper. Nevertheless, the importance of only one developer for both technologies is then highlighted to avoid a complicated regulatory procedure.

Simultaneously, regulatory conditions are very decisive. If the legislator stipulates through tendering that solar panels should be integrated into new wind farms, as is the case in the Netherlands, then the advantages and disadvantages mentioned above will play a subordinate role. Existing wind farms will probably be retrofitted much later because the pressure is lower. In general, it appears that some regulatory hurdles for both cases still need to be clarified, especially in Germany, where it has not even been clarified how to deal with multi-use.

6.3. The German (Spatial) Potential for and Advantages of Offshore Floating Photovoltaics and Multi-Use in Germany

The results show that an innovation requires political backing, economic expertise, and money, as well as knowledge about its environmental effects and the certainty about long viability to be implemented in the German EEZ. Even when all that would be given, an implementation would be easier if a wind farm is already owned by the company applying to install offshore floating photovoltaics with an existing concept for the interaction of both technologies. These results show that the current German regulations leave developer on their own and expect them to have solved every problem before trying to install an innovation in the German EEZ.

Nevertheless, the results of the thesis show that there is great potential for offshore floating photovoltaics in Germany. Especially in a country like Germany, where there are already many wind farms, and a lot of areas are reserved in the maritime spatial plan for future wind farms. Also, in between wind turbines, there is ample, unused, space. So, spatially, the potential of offshore FPV is great when integrating into offshore wind farms because it offers great potential for a higher energy yield per space and a better use of the grid's capacity. This is especially important because on land, but also increasingly at sea, there is space scarcity which, according to Przedrzymirska et al. (2018), validates multi-use.

In Germany, there are currently problems with the grid connection of offshore wind farms due to complicated processes and fractured responsibilities. Grid connections are therefore a huge challenge for developers. Offshore floating photovoltaics require no new grid connections because the cables etc. can be shared and can contribute to reaching Germany's energy transition targets, simultaneously, costs can be shared with FPV and OWF and the capacity of the grid increases. Therefore, the innovation can help reach targets by avoiding new grid connections and resulting problems.

6.4. The Barriers to an Implementation of Offshore Floating Photovoltaics and Multi-Use in Germany

The results indicate that there are currently many barriers to the implementation of offshore floating photovoltaics which belong to different categories. Particularly serious are barriers due to the immature technology, with technology readiness levels at a maximum of 7, and institutional barriers, which make implementation considerably more difficult. Regulations and laws need to be adapted to respond to many problems, which also arise from the multi-use of space, as the uncertainties are currently too great. For example, there are currently no regulations regarding possible curtailments. The uncertainty about environmental effects serves as a further barrier. An additional barrier is the lack of data, for example, the current tests of the technology are only undertaken in environments that do not match the "real" conditions far offshore, where the wind farms are located, and floating photovoltaics would be implemented.

The data collected during the interviews indicate that there is no clarity yet about the environmental effects of the innovation of offshore FPV and multi-use. It became evident that a lot of research is still necessary and that cumulative effects that arise due to the multi-use must be further investigated.

6.5. Recommendations to Overcome Barriers to an Implementation in Germany

The data shows that still great developments are necessary for the implementation of FPV, which are of a technological, institutional, financial, etc. nature. Furthermore, still more knowledge is required regarding the multi-use of space.

A lot is still needed for the niche innovation of offshore FPV in a multi-use space to take off. The barriers show that financial support and the provision of space could significantly accelerate the innovation and development of the technology. Similarly, research on the impact of the technology needs to be promoted to make a comprehensive impact assessment and thus to better know the consequences of the technology. In addition, increased awareness of multi-use and offshore FPV technology in politics could lead to faster implementation, as much can be moved quickly through politics.

To further promote and develop the technology and advance the knowledge about multi-use, Germany should facilitate the implementation of pilot projects. For this endeavour areas tendered in the site development plan that are dedicated to other energy generation could be used to combine offshore wind and solar and maybe also green hydrogen production. Germany could become an innovator and leader instead of being known as the country with the wait-and-see approach with too many bureaucratic hurdles to overcome. Overall, bureaucratic hurdles appear as institutional barriers and Germany should create shorter decision-making paths to facilitate the implementation of innovations and thus to reach ambitious energy targets faster and more easily.

The assessment of offshore floating photovoltaics in OWF shows that spatial, temporal, and provisioning dimensions overlap. Following the multi-use typology of Schupp et al. (2019), this can be categorized as either type 1 (multi-purpose/multi-functional) or 2 (Symbiotic use). Although there is no sharing of supply infrastructure the results show that the two technologies share their core infrastructure, namely cables and substations and therefore the two technologies are rather type 1 than type 2. If a multi-use of the first type is assumed, then it is suggested to provide financial incentives and securities at the policy level for the development of new technologies and possible combinations. On the regulatory level, it is recommended to develop and deploy joint licensing procedures for multi-use development throughout the entire life cycle. At the research level, the recommendations are to identify and address current gaps in knowledge about safety, benefits, and setbacks. On the industrial level, it is proposed to develop pilot sites to demonstrate and further develop the technology. In addition to the recommendations for individual types, general actions can be recommended. The results of this thesis show that there are significant gaps in policies and regulations, with the innovation currently not being addressed in the marine spatial plan. It is recommended to develop clear guidance and direction on integrating operational issues such as insurance (liability), safety and tax regimes (Schultz-Zehden, 2018). The data obtained also shows that funding is problematic. It is thus recommended to encourage targeted incentives and adjust sector-focused funding to consider MU and to encourage targeted funding for small-scale MUs, as well as to create new financial instruments and business models (ibid).

Overall, the barriers and the recommendations of this thesis show that there is, following Schultz-Zehden et al.'s (2018) results, the need for a paradigm shift to advance the development of multi-use that involves the willingness of policymakers, governmental authorities, businesses, investors, and other actors. Also, the need for clear regulations and planning frameworks for multi-use is confirmed by the results.

Currently, no regulation addresses the multi-use of the ocean in Germany. Therefore, there is a lot of uncertainty about it. Consequently, stakeholders are not incentivized to implement multiple uses in one area. The findings for Germany in this thesis are supported by Onyango et al. (2020) who stated that there is a lack of discernible advantages of MU, also impressed as little push and pull factors towards MU. They consequently suggested intervening with policies, regulations, incentives, skills, and technology to improve the potential and net effects of multi-use (ibid). Therefore, to facilitate and even promote multi-use there should be governmental action expressed in regulations, policies, and incentives.

A suggestion to overcome barriers was to create regulations, laws, and incentives for offshore FPV following the precedent of wind energy development. Regulations could then be set up in the EEG, where offshore wind and onshore floating PV are currently regulated. Feed-in-tariffs and other incentives could also be adapted to offshore solar. Further, the development of offshore wind shows the importance of lobbying work to strengthen political willingness. In addition to learning from wind energy, onshore floating PV could serve as a model for regulations of offshore PV. For onshore FPV, an implementation is allowed on water bodies that are not ecologically valuable and only 15 % of the area is allowed to be covered. The question to further investigate is whether wind farms are considered ecologically valuable areas before taking over onshore regulations.

To accelerate the implementation in Germany, Germany ought to learn from other countries like the Netherlands. The targets set by the Dutch government help to create a business case and a market size for offshore floating photovoltaics, this attracts investors and developers and gives them certainty. The Dutch targets are therefore a great example of how to promote the acceleration of the development and implementation of FPV. Hence, German regulations should be changed to set a target for a point in time to accelerate the development of FPV to meet energy transition targets. Furthermore, as Germany struggles with dealing with multi-use in marine spatial planning, German MSP-makers should take the Dutch and Belgian regulations as role models for their regulations. Besides, to promote the implementation of offshore FPV in wind farms, the tender system in Germany should be changed towards the integration of innovation as demonstrated by the Netherlands.

As mentioned before, an EU directive required all EU coastal countries to prepare a marine spatial plan with certain specifications, which was very successful. Therefore, the EU could set a target for multi-use, which then has to be adopted by the countries to accelerate the development.

Overall, it becomes clear that technological barriers still occur and that there are differences among the different developers. Furthermore, there are uncertainties about insurance, connection, etc. and ecological effects must be further investigated. To overcome that, collaboration among different stakeholders across borders and sectors should be strengthened. This saves money and accelerates the development of floating photovoltaics. Aligning methods and solving problems also benefits planners, who get more certainty.

6.6. Concluding Remarks

In conclusion, it became evident that with the current laws and regulations, that serve as institutional barriers, the implementation of offshore FPV in a multi-use context in Germany is very difficult. Together with barriers in technology development, finances, political willingness, and the lack of data, the implementation of offshore floating photovoltaics in Germany is estimated to take a long time – if the technology ever proves to be technologically and financially viable. However, it became also evident, that there are great opportunities and advantages of the FPV technology, especially when combined with offshore wind farms in Germany, where a great spatial potential arises due to many areas dedicated to offshore wind farms. It is also important to mention in this context that, in Germany, issues are currently being tackled with a wait-and-see approach and that there is a lack of capacity to deal with offshore FPV due to the political fixation on green hydrogen. In addition, there is a lack of knowledge about the multiple uses of space in Germany, although the advantages of this have been presented more than adequately in this thesis. The findings of this thesis are in unison with those of Schultz-Zehden et al. (2018) and Onyango et al. (2020) which show that there are limited incentive schemes and barriers that occur due to the regulatory and permitting processes.

Applying transition theory, it became evident that offshore floating photovoltaic in a multi-use context is indeed a niche innovation that is not mature nor established enough yet to challenge the regime. However, the innovation possesses the ability to improve the current regime of marine spatial planning with the improved use of space and energy infrastructure with multi-use without necessarily challenging existing practices such as the increased implementation of wind farms. Nonetheless, current practices for the German case including the tendering process and openness for innovation must be changed to provide grounds for the innovation. As Ryghaug (2021) highlights, to further sustainable innovations, the development of pilot and demonstration projects is key. Therefore, Germany should further those to benefit from the advantages of innovation at an early stage.

The barriers to the niche innovation FPV in a multi-use surrounding for Germany overlap with the barriers found by Masawabi et al. (2021) where for the Botswana case on the landscape level the lack of commitments of policymakers was very limiting. The lack of commitments of policymakers was also overserved in Germany, while the results show that with more political interest, like in the Netherlands, many barriers can easily and quickly be resolved. Masawabi et al.'s (2021) findings at the regime level, namely barriers in policy and regulation, governance, technical capacity, and finance and at the niche level lack of funding for research and development and inadequate and unreliable statistical data were limiting the rising of technology from the niche and were also detected for the German case. This abundance of barriers showcases why there is no implementation of the innovation of offshore floating photovoltaics in a multi-use context in Germany yet will remain a niche innovation until there is more knowledge on how to deal with multi-use of space because the BSH, as the approval authority, will only approve a technology once it is fully developed and the ecological impacts are known. Consequently, the technology of offshore floating photovoltaics will also remain a niche technology until it is fully developed and there are regulations for space sharing that also include how the systems can be connected.

Overall, it seems that Germany will not allow or even mandate the implementation of offshore floating photovoltaics in the foreseeable future due to bureaucratic hurdles. Yet all available technologies are needed to meet Germany's energy needs and at the same time become carbon neutral with energy from renewable resources.

To promote the innovation, further research is advised about the possibilities of multi-use in Germany, but also on the environmental effects. Further studies should investigate whether the current German institutions allow for multi-use and a grid connection of offshore floating solar. Additionally, it should be analysed how regulations from other countries and sectors could be translated into German regulations on offshore floating photovoltaics to efficiently adapt the institutional framework in Germany without the need to create completely new rules.

To conclude, it thus became evident that the innovation offers many advantages and there is a great spatial potential in Germany, the implementation however is estimated to take a long time due to many barriers – if the technology ever proves to be technological and financially viable.

7. Reflection

This chapter reflects upon the thesis and points out what went well and what did not. Furthermore, limitations are presented and what would be changed in hindsight. Lastly, it is discussed if the results appear convincing.

For this thesis, six interviews were conducted. Additional interview partners were contacted but not available or there was no reply. Therefore, not every important developer or energy company was included, although insights from them would have been valuable to get a broader picture of the topic. Only one interviewee came from a German permitting authority and shared their point of view which might be subjective and might not represent the viewpoint of the whole organisation. A second interviewee from that sector would have been beneficial to back the answers. So, in hindsight, it might have been better to conduct more interviews to have a more solid basis for the results. In addition, political representatives could have been asked how much they knew about the topic and possibly answered how the political will could be strengthened.

Furthermore, two studies about multi-use from the UBA and the BSH themselves were mentioned by interviewee L1. Further tries to find additional information online led nowhere, so both federal offices were contacted by e-mail. The UBA's only response to these enquiries was that they could not imagine that offshore FPVs could withstand the waves of the North Sea and that they could not help. A reply clarifying the current technical status of the technology was answered by forwarding the case, but there was never another reply. An email was also sent to the BSH for information on the studies and other topics such as the possibilities to change the tender process, regulatory and approval procedures, collaboration efforts with other countries and organisations, further details on the multi-use of offshore areas for fisheries and energy, obstacles to multi-use in the German EEZ, the legal framework for floating photovoltaic projects and the permissibility of multi-use in current laws was asked, but there was no response and thus there was neither the possibility to get additional information nor to confirm made claims.

After the first interview, it appeared, that the first questions were too broad, and the questions were thus adapted for the other interviews to not confuse the interviewees. It showed that questions should on the one hand be broad to not steer the interviewees, but also too broad questions might lead to confusion and further enquiries. Additionally, it went less well that the internet caused major problems in one interview, which made it difficult to understand.

The results and the complete answering of all questions show that the methodology with semi-structured interviews was suitable. It went well that the selected interviewees gave a wide range of answers and revealed many barriers, but also potential solutions.

Overall, the results and the outcome appear convincing to the author of this thesis, because there were many overlapping answers and pre-made assumptions were fulfilled. As Germany is known to be highly bureaucratic and slow with innovations, it was no surprise to find out that the same is true for offshore floating photovoltaics in a multi-use context.

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Appendix

I. Interview Guide

1. Introduce myself
2. Introduce my thesis
   a. Explanation along the structure
   b. Sub-questions
   c. What I want to achieve with the interviews
3. Ask org. questions:
   a. Consent for recording
   b. Name them in the thesis?
4. Ask them to introduce themselves and their relation to the topic
5. Start asking questions
6. Question: **big**: very important, grey: only ask if time is enough

Questions

- **What are your experiences with that technology?**
- What is your opinion on its feasibility?
- How relevant is the technology?
- Do you think there is an urgency to scale that technology up?
- What role will it play in the future energy system? Is the technology suitable to tackle future energy issues?

Floating photovoltaics

Only producers of FPV:

- What is the technology about?
- **How mature is the technology?**
- **Is the current state ready for implementation?**
  - **If not: why? What needs to change?**
- When do you think the technology is fit for the masses?
- Do you currently encounter any problems?
- What are the different types? Which do you think is the most suitable for mass production?
- Which areas are most suitable for that technology?
- What has a more severe impact? Technical issues, lack of data or institutional barriers?
- How much energy can you produce per space?
- **How much increase in Energy output in comparison to solely OWF? (For the specific technology they use)**
- How expensive would such a project be? When could it be profitable?

To one particular developer:

- Your system survived many strong storms, what do you think are the roughest conditions your system can handle/is designed for?
- Are there such conditions in the German North Sea?
    - (Question if waves, etc. might limit the implementation)
- **Later: I have seen that you work within the EU-Project EU-SCORES, what are your experiences? What went well, what not?**

Floating PV - everyone

- Do you think this is a niche technology or do you predict it to be more large-scale?
- **What are opportunities of the technology?**
- **What are the effects of that technology? Positive or negative?**
- What are the effects on marine ecology?
- Can negative effects be mitigated by making design adjustments?
- How to deal with uncertainty on long-term environmental impacts for permitting?
- Is a monitoring useful/necessary/required? Why?

MSP & Multi-use

- **What do you think about a multi-use of space for offshore floating photovoltaics?**
    - With what?
    - What about OWF?
        - Is every OWF suitable for an extension with FPV? Why? Why not?
- **What do you think is needed to integrate FPV into OWF?**
- **What about the (existing) infrastructure? Is it enough or is an extension necessary? (Cable pooling, balancing?)**
- **Better/easier an integration to existing OWF or a joint planning?**
- Would a combination with the upcoming floating wind farms also possible?
- **Where do you see the greatest barriers?**
- Could there be conflicts (with fisheries)? Because some areas are designated for OWF and fishery
- **Which variables/factors are important for an implementation?**
- Are you familiar with the MUSES project? If yes: What can be learned from projects like the MUSES project for the implementation?

Only DMEC

- What have you experienced during the EU-SCORES project?
- What went well, what not?
- What is/was the most difficult part?

Case of Germany

- Do you think that technology could help to reach Germany's energy targets?

- **What do you think about an implementation in Germany?**
- **Are there already plans for an implementation in Germany?**
  - If yes: How do they approach it? What are the first steps?
  - If not: why not? What would be necessary?
- **Where do you see the (spatial) potential?**
- Do you think an implementation would be possible with the current marine/maritime spatial plan in Germany?
- **What must change for a faster implementation?**
- What do you think must change politically/in legislation?
- Is there any funding eligible? Do you know any about subsidies, legal guidance? Any securities for developers?
  - If not: What should there be to start implementing in Germany?

End:

- **What are the most prominent barriers to implementation in your opinion?**
- **What needs to change for implementation?**
- **Is there anything I haven't asked that would be relevant?**
- **Concluding words? (Feasibility, potential, relevance)**

II. Coding

Table 2: Codebook with code categories, code names, code descriptions, code frequencies and examples for all codes that were used to code the transcribed interviews.

Code Category	Code name	Code description	Frequency	Example
Case Germany	Case Germany	Statements and answers that correspond with the German case and the status quo, potential and initiatives in Germany	36	"I really am not aware of any initiatives in Germany."
Case Germany	Planning Process	Statements regarding the planning process in the German EEZ	3	"So, we do everything on application. When we get the application documents and we say yes, that's understandable, that's good, you can imagine

				that, and you ask around and request more things if you think that's not enough.”
Technology	Technology adaptations	Possible adaptations of the technology to mitigate environmental effects	2	“Some people even think about having light lights under the panels, so you compensate the lack of sunlight.”
Technology	Technology facts	Given facts about the technology of FPV and its structure	5	“The whole system consists of a floating system on which PV panels are mounted the whole island or this floating solution is anchored to the bottom, of a sea lake.”
Technology	LCOE	Statements regarding the Levelized Costs of Energy of FPV	6	“But they target 250/€ megawatt hours. While us is two times more expensive. So, we are now at 500.”
Technology	Maturity/TRL	Information about the Maturity of the Technology expressed in the TRL	8	“We are now TRL seven, so that is technology readiness level seven, in which we have demonstrated the offshore possibilities of the technology for over a year. And we are also on the brink of setting the step to TRL eight, which I think we will have completed once we have installed and demonstrated

				offshore solar projects.”
Challenges	Challenges	Statements regarding current challenges in the development and implementation of FPV, also related to the multi-use and environmental concerns	27	“The challenges are all three challenges, so technically, regulatory and financially all three are quite solvable and we are also working on all of them.”
Potential/Advantages	Potential/ Advantages	Statements regarding the advantages and (spatial) potential of the FPV technology	25	“So, the biggest advantage of floating solar is scalability.”
Effects	Positive	Possible positive effects of FPV on its surrounding	10	“And what it can do is what I've heard and that's there's of course also a hypothesis that in in periods of extreme heat, though, we are looking at climate change already and we have very hot summers sometimes then a floating PV and give you cooler waters for fish.”
Effects	Negative and environmental	Possible negative effects and effects on the environment of FPV	31	“Here is of course the big question about the impact on the ecosystem, for example also on birds, because of course, drifting large turbines attract birds, while wind farms

				are not exactly the area where you want to have birds now. That is a problematic thing. What we are still investigating is, for example, the impact. But basically, the impact we see so far is relatively low or even positive with reef-building etcetera.”
Space/Locations	Space/ Locations	Information about the location of FPV in the EEZ and its implications	12	“The further offshore you go, the greater the cost of bringing the electricity onshore and at the same time the better it is to use the infrastructure as much as possible because that significantly reduces the cost per kilowatt hour that the state has to pay.”
FPV & OWF	Opportunities	Opportunities that the combination of FPV and OWF in one area offer	34	“If we look at areas where there is already quite a large offshore sector, such as the offshore wind sector, there is for example Germany, Denmark, the Netherlands, and Belgium. There, the biggest opportunity is actually that we have extremely much, we have

				extremely many wind search areas, we have extremely many wind farms, wind farms that are already being built. We don't have full utilisation of the network in these wind farms, the electricity network, which is financed by the state. Therefore, floating solar can help with that.“
FPV & OWF	Planning Process	Implications for the planning process of FPV and OWF in a multi-use context	14	“But in principle, I think that, for the future, it would be wise to do it as an integrated approach rather than include it afterwards. Okay. And also owned by one, I'd say, one project developer.”
FPV & OWF	Difficulties & Barriers	Possible difficulties and barriers that (might) occur when combining FPV and OWF	10	“And legally, when will what be curtailed if too much is produced? Who has priority? How does that cannibalise which business case? That is the problem when there are two project developers in an existing wind farm and a solar plant is added.”
Barriers	Technical	Technical barriers to the	6	“And then it's important that everything stays afloat and that

		implementation of FPV		the electrical components always work at that for a period of 20, 25 years long, because that's an above minimum period for a floating PV system or land, on a roof. So that should also be true for floating solar. And yeah, in order to make these systems stable for a period of 25 years, this is enormous challenging because the North Sea is very, very harsh and demanding."
Barriers	Financial/Funding	Financial barriers to the implementation of FPV	27	"I think of also financial issues, absolutely. Because projects need to be financed by banks or by investors. Yeah. They require always, I think if they want to minimise their risks. So that's what I mentioned in order to minimise risk, you have to make your technology bankable and prove that yes, what you promised will also come true, that you will have a system of and solution that will earn back

				the money, which is invested so absolutely, banks will be crucial in this whole development. And I think that's especially for companies like Ocean of Energy, which is a small company, in order to them to earn or to sell projects, I think they have to convince the banker and the investor that what they will produce is it will also get to give the return and that that's it's for every PV technology the case, so you have to prove and to convince the banker and investor that this is a good investment."
Barriers	Political/ Willingness	Political barriers and barriers in willingness to the implementation of FPV	9	"Of course, that also has to be the case, because if it's something new, like hydrogen, it probably won't be self-supporting from the start, but will need start-up financing, just like wind energy did at the beginning, and then, of course, the politicians have to back it up, that's clear.

				And also research, that is, that research funds go into it, that is, various ministries are involved in it."
Barriers	Institutional/ Regulatory	Institutional barriers to the implementation of FPV	14	"So that's on one hand and I think, there are a lot of legislation issues, I think that is always the case with permitting and legislation, grid connection, is there sufficient capacity from the grid operator to integrate also solar. And these are all, I would say, barriers to overcome."
Barriers	Lack of data	Barriers to the implementation of FPV related to the lack of data	48	"There is not one answer. And what I would try to make clear to you is that there is there is quite some research needed still, in order to fulfil these large ambitions that we all have. So, what, what and when and what are the factors determining the performance. So, what is determining the electricity outputs and what will be the influence of the movements on the electronic components?"
Barriers	Others/Testing/Insurance/etc.	Barriers to the implementation of FPV	19	"One of the challenges we do have is that, uh, uh, there's

		that cannot be categorized into the previous barrier categories		not that much availability for testing infrastructure. So, if we would be able to fund a project for a 30-megawatt offshore solar farm, we would have the challenge that we cannot really find a location where we can install an integrated 30 megawatts of offshore solar to the grid.”
Learning	Current projects	Statements and experiences from projects that allow learning for the German case	9	“We are in the Port of Oostend ready to assemble and integrate the top deck. And as from mid-August will start to install these at sea.”
Learning	From other countries	Statements and experiences from other countries that allow learning for the German case	17	“So, at first, we were quite concerned about how it was going to be implemented in policies. But now we have like this Dutch policy, I do think that the greatest barriers are resolved.”
Learning	From other sectors	Statements and experiences from other sectors that allow learning for the German case	13	“So, like, uh, with offshore wind, Europe is quite good in terms of industrial leadership. It's both in the wind turbines as well as in the installations, etc. like this, uh, these projects and financing,

				etc. So, I think there are lots of lessons learned from the offshore wind industry that can be applied to offshore solar.”
Proposed solutions	Proposed solutions	Proposed solutions from the interviewees to overcome barriers	40	“I think that in Europe, we, we must really consider to implement the vision. Every offshore wind farm, um, should be equipped with an equal installed capacity of offshore solar compared to an installed capacity of offshore wind farms. I think that would help us a lot with the energy transition and can really become a game changer.”