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How do fixed and floating offshore wind parks contribute towards the SDGs? An integrated quantitative and qualitative assessment of SDG impacts

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How do fixed and floating offshore wind parks contribute towards the SDGs? An integrated quantitative and qualitative assessment of SDG impacts

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Abstract. Offshore wind (OW) energy is crucial for global climate goals and sustainable development, yet its sustainability impacts extend beyond energy benefits and the locations where wind farms are installed. This study evaluates the sustainability implications of OW, comparing fixed and floating technologies using an integrated approach that combines input-output (IO) analysis, global value chain (GVC) assessment, and a qualitative Sustainable Development Goal (SDG) interlinkages assessment. The findings show that OW investment affects regions involved in material extraction, due to mining activities. This shows that a value chain perspective is essential to identify sustainability bottlenecks, such as material-related emissions, construction energy demand, and maintenance impacts, especially for floating OW. Despite its reduced seabed disturbance, floating OW's sustainability benefits are constrained by material use, particularly related to emissions from steel production. This study provides insights for improving OW sustainability, advocating for greener value chains, increased material circularity, and the adoption of lower-impact material alternatives. These findings inform future research and policy directions for more sustainable OW deployment at scale.

1 Introduction

The transition toward a climate-neutral economy necessitates ambitious emission reduction strategies, with large-scale offshore wind (OW) energy emerging as a key solution to meet global renewable energy targets. As of 2023, global OW capacity has reached 73.185 GW, yet achieving the 1.5°C goal requires a substantial scale-up to 494 GW by 2030 and 2,465 GW by 2050 [1]. This rapid expansion is not only crucial for limiting global temperature rise but also plays a pivotal role in advancing broader sustainability objectives. By accelerating the deployment of renewable energy infrastructure, OW directly supports Sustainable Development Goal (SDG) 7 Affordable and Clean Energy by expanding energy access, reducing dependence on fossil fuels, and fostering a more resilient and equitable energy system.

Over the last decades, most wind parks were installed in Europe and China. Together, the United Kingdom, Germany, Denmark, Belgium, and the Netherlands accounted for over 75% of globally installed offshore wind capacity. [2]. These wind parks are mostly installed in shallow waters, with water depths up to 50 meters, by using foundations fixed to the seabed [1]. An emerging technology in the industry, floating OW technology, can be installed in deep water, unlocking a huge resource potential for countries where water depths are higher than 50 meters and allowing installations farther away from shore in countries such as Norway,USA, United Kingdom and Japan [3]. Although mostly using the same turbines, floating technology is more than a simple extension of the current OW industry [3]. It is installed in a different environment, farther offshore, with specific logistic, technological and geographical conditions [1]. Consequently, the energy output, economic effects, and environmental impacts of floating OW technology differ from fixed technology [3, 4, 1, 5].

As the deployment of fixed and floating OW technologies accelerates, it is essential to assess their broader implications, as outlined by the Sustainable Development Goals (SDGs). Previous research has predominantly focused on the direct effects of OW on sustainability targets (see for example [6]), but assessing indirect, interlinked, and global effects is equally important [7], especially in industries with complex supply chains like OW. The production and deployment of OW infrastructure involve extensive material and energy inputs, creating unforeseen trade-offs across environmental, social, and economic dimensions. Moreover, OW faces a credibility challenge: while its primary objective is to provide sustainable and renewable energy, public opinion questions whether it is truly the more sustainable option. This debate underlines the importance of researching the OW industry to ensure its development aligns with long-term sustainability goals. A holistic sustainability assessment is therefore essential to identify both synergies and potential trade-offs, ensuring that OW development effectively supports the SDGs.

Despite the growing body of literature on OW energy, significant research gaps remain in comprehensively assessing its impacts on the SDGs and how these impacts subsequently interlink within the SDG framework. Most existing studies focus on specific SDGs [6] or isolated sustainability aspects [5], rather than providing a holistic analysis of how the future uptake of OW energy globally impacts the broader sustainability agenda. Additionally, to our knowledge, previous research has not differentiated how both floating and fixed foundation technology impact the different sustainability dimensions outlined in the SDGs. However, the distinct characteristics of these technologies –such as infrastructure, components, location, and materials– result in varying sustainability impacts. No previous studies have systematically evaluated how these two OW types differ in their economic, environmental, and social implications. Addressing these gaps is particularly relevant as floating OW is not yet a mature and dominant technology, making it crucial to estimate the impacts of deploying this technology at scale.

This research aims to assess the impacts of a global uptake of OW energy on the SDGs. By means of that, we take into account the future scenarios of the global OW industry, based on policy briefs and public intentions by analyzing government strategies, roadmaps, and relevant projections. By combining input-output (IO) analysis with global value chain (GVC) analysis, we take into account where wind parks will be installed, where materials come from and where the main suppliers are located to measure the global impacts of both fixed and floating technology on the SDGs. To account for the interlinked and non-quantifiable effects in the context of floating and fixed OW technology, we use the qualitative SDG interlinkages method of focus groups and existing literature. By assessing the direct and indirect impacts on the SDGs by IO analysis and the interlinked effects by the qualitative method, we aim to tell a comprehensive storyline of how floating and fixed OW technologies impact the SDGs.

2 Background

2.1 Value chain of offshore wind

Typically, OW value chains are distinguished as two interconnected parts with different lead firms: the manufacturing (i.e. investment) value chain and the deployment (i.e. operations) value chain [8]. The manufacturing value chain is concerned with designing and building the key equipment and installation work including logistics services and establishment of substations and grid connections [9]. Major groups of actors in this value chain are equipment (such as turbine) manufacturers, component suppliers, consultancy and design services providers. The deployment/operations value chain focuses on the use phase and comprises operations and maintenance services, administration/site management, financial services (insurance and financing) and sales. Additional infrastructure might be necessary to connect the wind farm to the grid and to ensure grid balance. These activities are typically led by wind farm developers and operators. Major groups of actors are firms concerned with planning, construction and logistics, operations and maintenance service providers, and utility companies, (independent) project developers and financial investors. Interconnections between the two value chains consist through, e.g., turbine manufacturers (in the deployment chain, they may deliver operations and maintenance services) and wind farm owners (they may demand specific components/technical specifications etc.) [8].

Some actors, such as utility companies operating a wind farm, are more location bound and tend to stay close to their home markets while other actors such as financial investors have a rather global orientation. Component suppliers and large equipment manufacturers often operate globally via subdivisions or similar strategies to be close to wind farm operations [10]. For example, manufacturing of blades and foundations for OW farms is currently a very concentrated market with main production in Denmark, Spain, the US, and China. This market concentration is expected to persist over the next decade, with China emerging as the dominant supplier for the Asia-Pacific market.

To understand the wider socio-economic impacts of renewable energy and OW technologies, researchers have exploited the value chain structure represented in Input-Output (IO) models. The IO methodology allows for analysis on how one sector stimulates production in other sectors via the economic structure of production. For instance, The Jobs and Economic Development Impact (JEDI) models, based on IO principles, are widely applied in the U.S. with the study of [11] focusing on job creation in OW deployment. [12] examined the economic effects of expanding Scottish marine energy using both IO and general equilibrium models.[13] conducted a sustainability analysis of onshore and OW energy systems using IO modeling.

2.2 Material requirements

The production of wind turbines and the construction of OW farms are material intensive. Metal ores, such as iron, copper, lead and chromium, account for about 90% of all materials required. China mines about 80% of rare earth metals and dominates the market for refining these metals and the manufacturing of permanent magnets for green technologies, with North America playing a minor role [14, 15]. This dependence on rare earth metals is only increasing, since new generation turbines use magnets. As the wind turbines become larger over the coming years, with an expected average turbine capacity of 15 MW in 2040, more bulk materials are required to build the support structures [16]. [16] estimated that this increasing size implies a 50-fold expansion of low-alloyed steel, high-alloyed steel, iron and concrete compared to current demands. Similarly, the cumulative demand for the needed key metals might increase by 85%.

2.3 Floating technology

For floating turbines, some differences in the value chain exist compared to the traditional fixed foundations, especially related to the logistics, installation and components and materials used for the foundations. The turbines used for floating technology are the same (with minor modifications) as for fixed [1]. However, for the foundations, there are four major categories: spar (including articulated multi-spar), barge, semi-submersible ("semi-sub") and tension-leg platform [17]. There is not clear consensus on preferences within the industry, but semi-sub and spar-buoy technologies are the most mature with a technology readiness level (TRL) of 8-9 [1].

For the floating foundations, depending on the type, the main raw materials that are used are mostly steel and small proportions of concrete [1, 16]. Because of the high amounts of steel, the impacts of the material extraction of floating foundations are relatively high [18]. Compared to fixed foundations, floating foundations require more materials in order to make them balance and float correctly [19]. Therefore, floating solutions that allow to limit the overall weight, such as the tension-leg-platform, have considerably lower material demands [20].

In addition to the floating foundation, multiple components are needed specifically for floating technology. The mooring system, including the mooring lines and anchors are the key components to maintain and control the position of the foundation. The mooring lines connect the foundation to the anchor, which secures the floating foundation to the seabed. These anchors allow "sharing", meaning that multiple foundations can be connected to a single anchor [1]. For floating foundations, cables to transport the electricity are heavier and larger, leading to the fact that special equipment is needed [21]. These cables are developed specifically to withstand the conditions far offshore and can be dynamic in order to follow and withstand the motion of the floating structure [1].

For the installation, the water depths and longer distances to shore complicates the construction of the turbines. The impact of weather conditions farther offshore is larger, which can significantly increase costs and downtime [22]. In addition, floating turbine components are constructed near shore and specialized vessels are needed for the mooring and anchor and to transport the components to location. Hence, dedicated floating OW port facilities are necessary to ensure they are suitable for the specialized large vessels for mooring and anchors as well as the assembly of components [23].

3 Method

3.1 Multi-regional Input-Output analysis

For the quantitative analysis of the impacts along global value chains we utilize multi-regional input-output (MRIO) analysis [24, 25, 26] based on the OECDs inter-country input-output tables [27, 28]. These tables show, in monetary terms, the trade in intermediate goods and services between 45 aggregated industries and 77 countries as well as the use of final goods and services by households, governments, and investments by industry. Using the demand-driven input-output model [29], it is possible to identify where in the world production with all its implications on employment, material use, emissions etc. occurs due to the demand for final goods and services.

Let $\mathbf{A}$ be the matrix of inter-industry requirements, where each column and each row in the matrix represents one industry in one country. The data in the column corresponding to industry j then show the inputs needed by industry j from all other industries in all other countries. More specifically, entry a_{ij} represents the share of inputs from industry i needed by industry j to produce one unit of output. Final demand for goods and services by the final consumers is usually represented by a vector $\mathbf{y}^{fc}$ where the f corresponds to the different types of final consumers (household, government, investment) in the different countries c. Entry y_i^{fc} is the demand for good/service i by final consumer fc. Global production by industry, vector $\mathbf{x}$, can then be calculated by

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \sum_{fc} \mathbf{y}^{fc} \tag{1}$$

with $\mathbf{I}$ being an identity matrix of appropriate size. Employment, emissions, or material etc. associated with industrial production can then be calculated as

$$\mathbf{f}^e = \hat{\mathbf{s}}^e (I - \mathbf{A})^{-1} \sum_{fc} \mathbf{y}^{fc} \tag{2}$$

where $\hat{\mathbf{s}^e}$ is the diagonalized vector $\mathbf{s}^e$, with entries s_i^e representing the number of employees or the amount of emissions or materials or other global value chain (GVC) indicators (denoted by e) needed by industry i to produce one unit of its goods or services. A full list of GVC indicators used here is available in Table SI2 in the Supplementary Information. For the construction of the satellite account data we used both the OECD-ICIO data [28] and the satellite accounts from the Gloria database [30], as explained in more detail in [31]. We define the GVC indicators from the database for the year 2020 as the 'Baseline'.

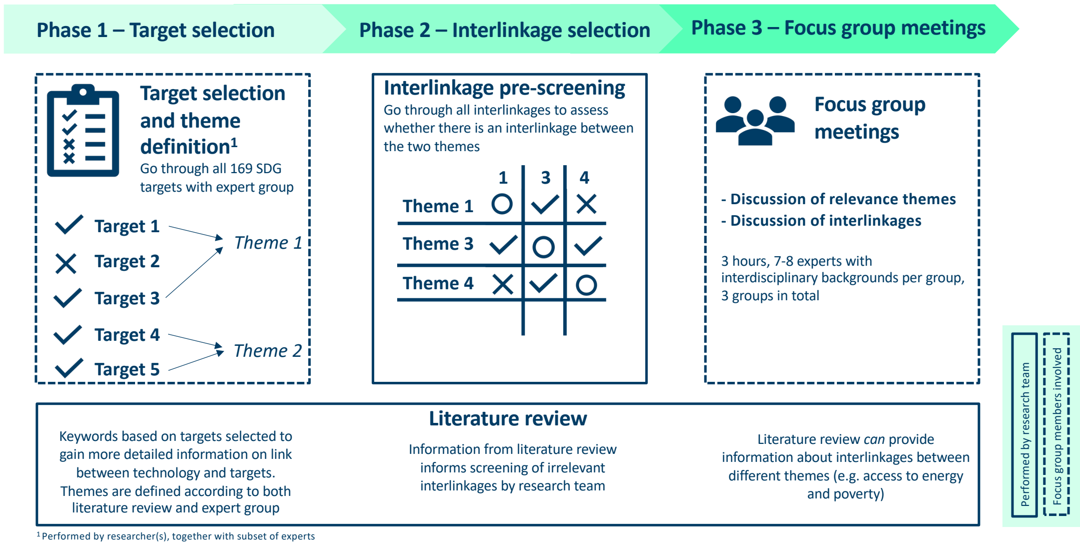
We then construct two investment vectors, $\mathbf{y}^{\mathbf{fixed}}$ and $\mathbf{y}^{\mathbf{floating}}$ that show which goods and services are needed from all industries in all countries to build the offshore wind parks globally over the next decade or so. We then recalculate $\mathbf{f}^e$ for all e as $\mathbf{f}^{e,fixed} = \hat{\mathbf{s}}^e(I - \mathbf{A})^{-1}\mathbf{y}^{fixed}$ and $\mathbf{f}^{e,floating} = \hat{\mathbf{s}}^e(I - \mathbf{A})^{-1}\mathbf{y}^{floating}$.

From the GVC indicators it is possible to estimate more than 30 SDG indicators [31], see Table SI3 in the Supplementary Information. To compare the impacts of investments in fixed or floating offshore winds along global value chains, we calculate the difference between the SDG indicators calculated from the $\mathbf{f}^{e,fixed}$s and the $\mathbf{f}^{e,floating}$s relative to the SDG indicators calculated from the 'Baseline' $\mathbf{f}^e$s. The results should then be read as '*Cumulative impacts on the SDGs over the next 10 years compared to the base year 2020*'.

While extensive data exists for fixed OW, floating OW relies mainly on estimations and projections. Since our analysis focuses on global impacts, we do not account for location-specific cost variations due to geographical and meteorological factors. Instead, we use average investment estimates for fixed OW and projections for floating OW costs from [32].

To construct OW scenarios, we identified countries planning deployment by analyzing government strategies, roadmaps, and relevant projections while incorporating country-specific details. We derived

Figure 1: SDG interlinkages method



technology input coefficients, location data, and investment estimates from existing literature [33, 34, 32, 1]. Additionally, we assumed that maintenance and operational services are provided locally and that the market distribution of key wind farm suppliers remains unchanged. Finally, we compared two scenarios: one where all planned OW deployment uses fixed foundations and another where all deployment utilizes floating technology.

When examining the expenses required to implement OW, the majority of costs are capital expenditures (CAPEX), which is typical for wind energy projects regardless of the technology, as the bulk of costs lie in initial construction and installation. The operational expenses (OPEX) are relatively low in comparison and primarily relate to operation and maintenance costs. For the purposes of the quantitative part of this study, as we are analyzing aggregate effects on SDGs, we have assumed that OPEX costs remain the same between floating and fixed technologies, while the main differences lie in investment costs (CAPEX).

3.2 SDG interlinkages method

For the qualitative interlinkages method, we follow the approach outlined in [35], with the addition that we integrated existing literature throughout all phases of the process. An overview of the full method is provided in Figure 1. As a starting point, all 17 SDGs and 169 targets were considered. Several filtering steps were performed (a target selection session, a literature search, and a filtering session) to identify those targets and interlinkages most relevant to the offshore wind (OW) context. This process resulted in the inclusion of 20 themes related to the SDG targets, covering environmental, social, and economic dimensions.

To ensure consistency across methods, these 20 themes were aligned with the aforementioned indicator set (see Table SI2) used in the MRIO model. While the qualitative analysis was carried out at the SDG target level, the MRIO results were assessed at the indicator level. These (indirect) impacts captured by the IO method are in some cases "interlinked" by nature. For example, indicator 3.4 connects local emissions with chronic respiratory disease, reflecting a built-in relationship between environmental and health outcomes. In contrast, the interlinkages method was used to identify technology-specific interactions that go beyond the general interlinkages embedded in the SDG framework. Rather than representing the same interlinkages one-to-one, the two methods are complementary.

To explore the interconnections between these themes, three focus group sessions were held (each lasting approximately three hours), involving a total of 21 experts. Participants were selected through purposive sampling to ensure a wide range of disciplinary backgrounds and professional perspectives relevant to offshore wind and sustainability. The focus groups were deliberately composed to be interdisciplinary, enabling cross-sectoral discussion and ensuring that a diverse range of views was represented in each session.

Participants included researchers and professionals with expertise in marine biology, environmental sciences, engineering, geospatial analysis, applied physics, sustainability, social sciences, law, and energy policy. Several had extensive experience in offshore industries or environmental regulation, while others contributed knowledge in areas such as circular economy, impact assessment, hydrodynamics, and wind energy systems. The group comprised individuals working across academia, research institutes, industry, and advisory roles, ensuring both technical and socio-environmental dimensions were represented.

The selected experts were fully prepared prior to participation. A preparation package was distributed, containing background reading materials on the SDG framework and specific contextual information related to OW. The focus group sessions took place in person in 2024 and followed a semi-structured format. The central question guiding the discussions was: "Considering the link of OW towards theme X, how does this influence progress towards theme Y?" Additional sub-questions were introduced to support dialogue and, when relevant, participants were asked to reflect on differences between floating and fixed OW technologies. A moderator facilitated the discussions to ensure inclusive participation across all attendees.

All focus group meetings were audio-recorded, fully transcribed, and analyzed using an abductive approach. The study design was reviewed and approved by the Norwegian Agency for Shared Services in Education and Research to ensure compliance with data collection requirements. All participants provided informed consent prior to participation and explicitly agreed to the recording and anonymous transcription of the discussions. Transcripts were anonymized, and all data handling complied with GDPR and institutional ethical guidelines.

The coding process began with open coding, after which axial coding was applied to identify relationships among the concepts [36]. While the coding framework drew on the language of the SDG targets, additional themes and categories also emerged inductively. Following the qualitative analysis, supporting literature was consulted to further refine and substantiate the identified interlinkages.

4 Results and discussion

A full overview of all the results of each SDG can be found in Table SI1 in the Supplementary Information (SI). We differentiate our results in multiple ways. First, we estimated the impacts on both the investment value chain (CAPEX) and the deployment value chain (OPEX), across different regions for the available indicators. The investment effects are shown as a percentage of today's economic activity and related employment and emissions. These detailed results can be found in Appendix A in Figures 4 and 5 and are described in 4.1. Second, we identified trade-offs and synergies (using the SDG interlinkages method) that emerge from the direct and indirect impacts[1] of offshore wind on the SDGs, as shown in Table 1 (which is derived from Table SI1 in the SI) and further contextualized by integrating current literature in 4.1. Third, we estimated the impacts of building floating versus fixed OW farms (CAPEX) (see Figure 2 and Figure SI4 in the SI) accordingly and identified the different impacts of floating versus fixed in more detail, as shown in Figure 3. This is described in 4.2.

4.1 Global impacts of offshore wind technology on the SDGs

4.1.1 Regional effects Increasingly deploying OW is a means to reaching SDG 7 Affordable and Clean Energy. Energy access and cheaper and cleaner energy are, in fact, central to achieving multiple other SDGs. Although the impacts of CAPEX are largest where the suppliers are located and where wind farms will be built (Europe and Asia), we found that regions where OW is not installed are also impacted. This is especially in Africa and countries in Latin America (e.g. Chile), i.e. where the needed materials are mined. These negative impacts are the largest related to material footprint, GHG emissions and CO_2 emissions. In addition, high-skilled employment is increasing in regions where suppliers are located. For OPEX, the effects are largest where wind parks are installed (Europe and Asia). The operation of wind farms requires more business services and manufactured parts and less mining activities than fossil fuels. These economic effects together with the decrease in energy mining and CO_2/GHG emissions (i.e. SDG 13) are the strongest positive effects on the SDGs, which is supported by [13].

4.1.2 Social SDGs Related to the social SDGs, we found that these are less strongly affected than the economic and environmental SDGs. Most jobs created are high-skilled jobs (as supported by [37, 38]),

[1]These direct and indirect impacts were based on Phase 1 of the interlinkages method, together with the results of the MRIO analysis. In some cases, an direct/indirect impact was clear, but it was not included in the MRIO analysis due to data limitations, e.g. bird collisions

Table 1: Global impacts of offshore wind on selected SDGs

	(In-)direct impact compared to baseline	**Trade-offs (T) or Synergies (S) towards other SDGs in OW context identified in focus groups**
	Social effects	
SDG 1 No Poverty	+ Less people below international poverty line (CAPEX)	
SDG 4 Quality Education	+ Increased demand for high-skilled leads to increased education and training (CAPEX)	
	Manufacturing and production effects	
SDG 8 Decent Work and Economic Growth	+ Annual growth of real GDP per capita and employed person + Lower material footprint and material consumption + Economic growth and resource decoupling	T: Increasing size of turbines need more material extraction and is not more energy efficient (7,12,15)
SDG 9 Industry Innovation and Infrastructure	+ Manufacturing value added and employment – CO_2 emissions per unit of value added increase CAPEX + Less CO_2 emissions per value added OPEX – Premature retirement of fossil energy infrastructure + More high-skilled employment	T: Visual impact on tourism (8); Pollution and impacts on seabed and marine life (14); Waste generation, lack of recycling practices and material efficiency (12); Increasing size worsens labor conditions (8); O&G industry losing jobs, local community heavily affected (8) S: Biodiversity due to artificial reefs (15); Large supply chain creates high variety of jobs (8); Job creation and education will continue as industry matures (8,4)
SDG 12 Responsible Consumption and Production	– Higher material footprint CAPEX + Lower material footprint and material consumption OPEX + Less hazardous waste + Slower depletion of natural resources – Higher share value added in energy mining in total value added	T: Increase in material demand impacts labor conditions (8); T: lack of recycling (landfilling) impacts biodiversity (15); More recycling increases price, negatively impacting access (7); Large mix of materials makes it harder to recycle (12); Paint and contaminants in the water (14)
	Environmental effects	
SDG 14 Life Below Water	– Competition with marine activities (e.g. fishing) – Impacts mammals and fish populations and seabed	T: Soil profile and ecosystem changes, impacts fish populations and fisheries (14); Negative impact on job creation related to fisheries and tourism (8) S: Less use of fishing methods like trawling, good for biodiversity (14,15), opens the way for more sustainable fishing (marine protected areas) (14)
SDG 15 Life on Land	+ Reduced degraded land (from mining) – Bird collisions	

+ indicates positive impact on the SDG, – indicates negative impact on the SDG

especially jobs typically held by women (SDG 5) and subsequently training and education are in higher demand [39], positively impacting SDG 4 Quality Education. However, we see that building OW farms also creates jobs for low-skilled workers, which may positively affect income of the poorest (SDG 1). However, these jobs are concentrated where the suppliers are located, and very few jobs are created in Latin America and African countries. OW technology is also proving to be beneficial for Small Island Developing States (SIDS) because of their susceptibility to climate change, their resource limitations and the heavy reliance on imported fossil fuels [6, 40, 41].

4.1.3 Manufacturing and production SDGs For the targets related to SDG 8 Decent Work and Economic Growth, we found positive impacts on GDP growth and employment. The increase in employment is larger than the increase in GDP, indicating a switch from capital intense to labor intense industries. In addition, the extensive and complex supply chain of OW [12] creates synergistic effects related to job creation, as it fosters a diverse range of employment opportunities. This also relates to the positive impact on SDG 9 related to the increased manufacturing value added and (high-skilled) employment. This job creation, along with related educational advancements, is expected to continue as the industry matures. According to our findings, most jobs will likely be created during the construction of OW (as supported by [33, 39]), and only a small number of jobs will be created during the operations of OW. However, [12] found a significant number of direct, indirect and induced jobs being created during the operations and maintenance phase. To fully reap the benefits, it is important to include the local community [12], as

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the premature retirement of fossil energy infrastructure impacts the local job creation in the oil and gas sector. Previous studies have stressed the importance of the inclusion of the local community and [42] found that significant impacts on employment can be realized if benefit sharing of wind farm profits with the local government is implemented. This is supported by [12], who estimated that the use of more local content is accompanied by a 40% expected increase in value added and employment.

While OW development generates economic and employment benefits, OW is not a "one size fits all" solution [33]. The large-scale deployment of OW farms requires significant material inputs, and our results indicate substantial negative impacts during the construction of OW farms, reflected by a higher material footprint and increased CO_2 emissions. According to [43, 44], 40-80% of the environmental impacts of OW technology happens during the extraction and transformation of raw materials for manufacturing and repairing electrical grids and wind turbines. In addition, when the construction of OW farms is still using fossil energy (especially in the transport related to the construction [12]), there is also a higher share of value added in energy mining in the total value added.

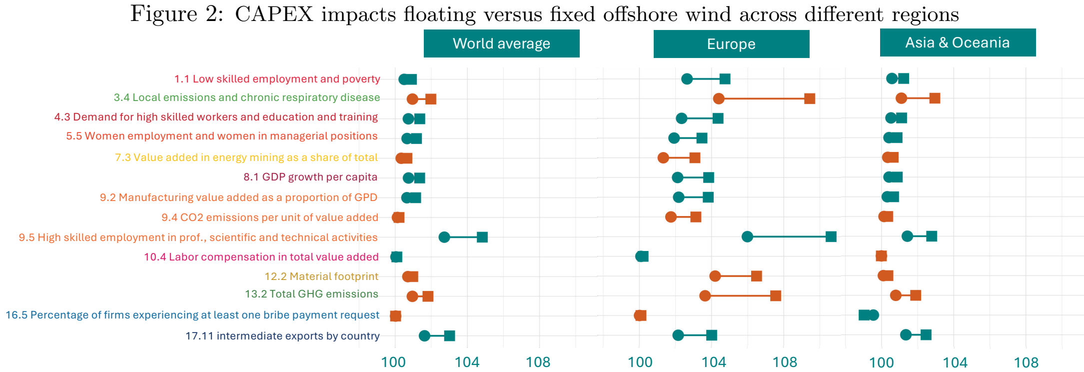
The continuous trend of the increasing size of wind turbines – a 16% increase in turbine capacity per year [45] – poses significant trade-offs regarding material use [46] and circularity. Although larger turbines have higher capacity factors, beyond a certain equilibrium, they are not necessarily more energy efficient [47]. The increasing size also affects labor conditions, as taller turbines require workers to climb more frequently, leading to greater physical strain, the most commonly reported issue in the sector [48]. More broadly, the energy transition is integrally linked to workforce health and safety, with risks such as toxic material exposure during the extraction and manufacturing processes, as seen across many technology-based industries [49].

Effective end-of-life waste management in the OW industry remains one of the industry's greatest challenges. By 2030, around 35 million tons of waste from decommissioned turbines are expected to require recycling – with the potential recovery of between 100 and 240 tons of steel, copper, aluminum, and glass fiber per megawatt of capacity – underscoring the urgent need for enhanced circularity [1]. This substantial waste volume is aggravated by the complexity of reusing OW foundations and structures. Although the foundations may last up to 100 years, the turbines themselves only last for 20–25 years [50]. However, retrofitting foundations to support larger, next-generation turbines is largely unfeasible due to both design limitations and limited industry standardization [51]. Moreover, decommissioning of OW farms is seen as one of the most disruptive and impacting activities [5], especially considering that marine life requires several years to restore itself after the construction of OW, only to be disturbed once again during decommissioning. Not only technical characteristics hamper implementation of circularity in the OW sector, other challenges also arise, especially related to the higher costs of circularity [52, 53]. This leads to significant impacts due to waste being landfilled, pollution in the water (through the dispersion of paint and contaminants), while recycling is further challenged by the diverse mix of materials [54]. As the first OW farms approach the end of their operational lifespans [55], there is also a growing focus on mitigating the environmental impacts of high-impact materials by replacing them with less harmful, biodegradable, and reusable alternatives incorporating natural compounds [52].

However, while the material extraction and labor-intensive aspects of wind turbine production pose challenges, OW energy ultimately leads to a lower material footprint and reduced resource consumption in the long run. Once operational, OW farms require significantly fewer raw materials compared to the baseline scenario of fossil fuel energy. This, in turn, contributes to decoupling economic activities from resource use, leading to several environmental benefits, such as reduced hazardous waste generation and a slower depletion of natural resources. This is what [12] called the "double dividend": simultaneous and substantial reductions in emissions while improving economic activity.

4.1.4 Environmental SDGs Both the building and operations of OW farms has large impacts on life below water (SDG 14). It impacts mammals and fish populations during both construction and operations. These impacts are described in more detail in section 4.2. In addition, OW farms impact areas used for fishing, which is one of the most heavily impacted stakeholder groups. This is not only related to the area competition, but also to the fish populations as the soil profile and ecosystem changes when wind farms are installed [6, 56]. In addition, fishing methods like trawling cannot be used close to wind farms. Though this negatively impacts fisheries, it opens the way for more sustainable fishing, leading to marine protected areas and improved biodiversity in the long-term [57]. Looking into the environmental impacts on land (SDG 15), we find long-term positive impacts because less mining is used (compared to the baseline scenario), leading to reduced degraded land. However, bird collisions and habitat loss by avoidance associated with the operations of OW farms are a significant negative impact [58].

Figure 2: CAPEX impacts floating versus fixed offshore wind across different regions



Circle is fixed foundation technology, square is floating foundation technology.
Orange indicates a negative impact towards the SDG, green indicates a positive impact towards the SDG. All values are shown relative to a baseline of 100, which represents the current electricity mix; deviations reflect percentage change from this baseline.

4.2 Floating versus fixed

4.2.1 Environmental SDGs As shown in Figure 2, we found that floating OW has higher environmental impacts compared to fixed OW technology during CAPEX, which can be seen from the increase in CO_2 emissions (SDG 3 & 9), GHG emissions (SDG 13) and energy mining (SDG 7). These effects are largest in Europe and Asia, as that is where OW farms will be mostly built and where suppliers come from. This increase is mostly driven by the materials used for floating technology, as these consist of more high-impact materials, with steel being the highest contributor [18]. Lately, there has been a push towards using concrete, which can reduce the material cost by 50% and lead to 40-50% lower CO_2 emissions [59]. Challenges with using concrete are the durability in marine environments and the environmental impacts of cementitious materials when deployed at sea [59]. Not only the type of materials used have substantial environment impact, also the amount of materials are higher for floating OW because of its more complex infrastructure [18], and the ballasting. Using more concrete could decrease materials used (especially for the ballasting), since it was estimated that the weight after ballasting of the entire turbine using steel was approximately the same weight, even though the concrete platform was almost four time heavier than the steel one [59, 60]. Another important factor to consider is the emissions due to the maintenance. If these mostly take place onshore, this will have major impact on emissions, depending on the vessel types (i.e. emission-free or fossil fuel driven) which are used to tow turbine parts to shore for major repairs [61]. However, these negative impacts are (partly) compensated by the higher capacity factor (reaching 50%) of floating OW.

Including the end-of-life scenario and circularity factor of OW is very important when assessing the overall environmental impact, especially with regards to the recycled materials [19]. Although steel production generates significant emissions, its high reuse and recycling rates contribute to advancing circularity, emphasizing the need to increase the use of recycled steel content [18]. Additionally, floating OW in general supports circularity since their foundations can be disassembled more easily and cleanly at the end of their life cycle, leaving behind minimal material waste and promoting efficient material recovery [51]. As mentioned by [5], the floating structures and the chains can be recycled on land, while the anchors can be eventually left in situ to not disrupt the artificial reefs. These structures also serve as deterrents for trawling and fishing, with long-term positive ecological effects. However, the water depth and distance to shore have significant impact on the decommissioning costs, and there remain high uncertainties in the estimations because of the immaturity of the technology [51].

The largest differences between floating versus fixed foundations can be seen on the impacts on marine life (SDG 14). Looking at the positive impacts, the structure of floating foundations in itself has less impacts on the seabed, having a smaller footprint since only the anchors directly contact the seabed. Because floating OW does not need foundations and pile driving, it significantly reduces the impacts of noise during construction [5]. However, the differences between impacts of noise during operations of floating versus fixed are still unknown [62]. The location and placement of floating OW also leads to lower vessel collisions. In addition, compared to fixed-bottom OW farms, which can increase local water mixing by 7–10% up to 1 km away, floating OW farms likely have a much smaller influence on water column dynamics (i.e. more local) due to the absence of the fixed foundations [5]. Similarly, the wake

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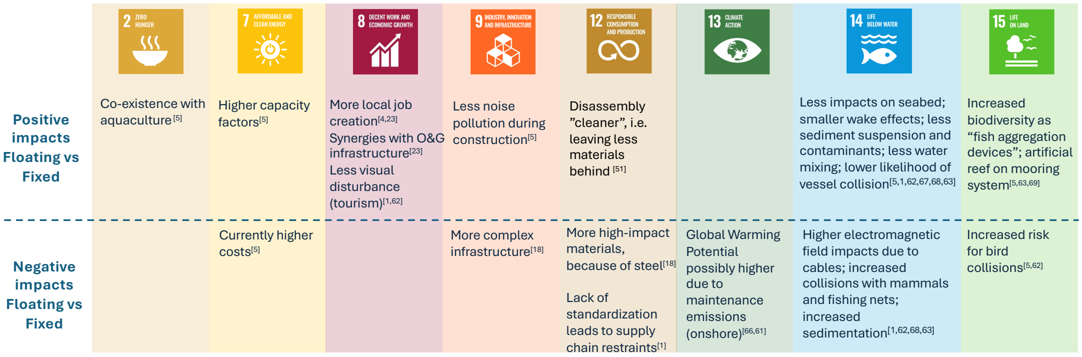
Figure 3: Differences in impacts of floating versus fixed offshore wind on the SDGs



effects of floating OW are lower due to the smaller seabed disturbances and weaker deep-water currents [63]. In addition, if floating foundations use embedded anchors, suction caissons and dead weight anchors, there is less sediment suspension (i.e. when particles are lifted from the seabed and remain floating in the water column due to turbulence) and consequently release less contaminants [1].

While floating structures may have less sediment suspension, it may increase sedimentation (i.e. when the suspended particles settle back down and accumulate on the seabed), because of the anchors and components being impacted by wave action and currents) [64, 62], negatively affecting benthic fish populations [65]. In addition, floating OW needs a significant amount of cables for the power generated to be transmitted to shore, leading to higher electromagnetic field impacts [63]. There is also increased entanglement for mammals, both directly into the mooring lines, or indirectly into the fishing nets that are stuck in the mooring lines [1, 63].

Given the size of a floating OW farm, they can serve as marine protected areas, significantly enhancing biodiversity (SDG 15) and allowing for restoration of degraded areas [5]. The mooring lines and floating substructures can also act as fish aggregation devices and artificial reefs [66]. Although many long term impacts are still unknown related to habitat alterations, it is expected that floating OW farms are unlikely to present many novel challenges [63]. A potentially (and more significant compared to fixed OW) negative impact on SDG 15 is related to bird collisions. Given that the development of floating OW turbines is associated with an increase in size, there is an increased risk of collisions for birds and bats [5]. Although seabird presence generally decreases farther offshore, because of the higher wind speeds behaviors also change farther offshore. This leads to birds relying more on gliding and flap-gliding and seabirds using these techniques may have more difficulties avoiding turbines [62].

4.2.2 Manufacturing and production SDGs Floating OW projects present significant opportunities for local job creation, particularly due to their reliance on port-based assembly rather than offshore construction [23]. This reduces the need for expensive offshore construction activities and enables greater use of local labor and resources [23]. As previously discussed, ensuring local community inclusion is crucial for maximizing the socio-economic benefits of OW, particularly in regions affected by the transition away from fossil fuels [12, 42]. To meet the logistical demands, ports need to be expanded and upgraded, leading to infrastructure investment and additional employment opportunities. Furthermore, local procurement plays a key role in job creation, as developers benefit from sourcing components near assembly points to reduce transport costs and ensure material availability, especially given the weight and number of components [23]. Compared to fixed structures, floating OW require a higher number of workers and generate higher impacts on value added (as shown in Figure 2, on 9.2 Manufacturing value added as a proportion of GPD), primarily due to their higher investment needs [4].

Floating OW can also provide opportunities to transition offshore oil and gas (O&G) reliant economies toward renewable energy employment. OW in general, but floating technology in particular, leverages many of the skills, expertise and infrastructure already establish in the O&G sector. For instance, the mooring systems for floating OW draw directly from offshore O&G experience [67] and synergies between the offshore O&G industry and OW industry can help reduce costs and address transmission challenges [3]. The reuse of offshore O&G infrastructure, expertise, and workforce means that regions that traditionally relied on fossil fuel industries can transition into stable, long-term jobs in the renewable energy sector, ensuring that these regions maintain economic resilience while moving toward a sustainable future [68].

Beyond energy production, floating OW development opens opportunities for offshore aquaculture, which could further drive job creation in coastal communities. Aquaculture operations within floating OW areas have been identified as a promising way to co-locate sustainable food production (SDG 2) with renewable energy generation, particularly for seaweeds and bivalves, which have minimal environmental impacts [5]. Furthermore, the integration of offshore aquaculture with floating OW allows for the sharing of infrastructure and vessel supply chains, reducing costs and enhancing the economic feasibility of both industries [5]. This synergy could provide alternative employment pathways for workers transitioning from traditional fisheries, transforming the sector into a more sustainable and productive industry. Additionally, floating OW has lower visual impacts (as it is installed further offshore) compared to fixed OW, making it more compatible with eco-tourism initiatives, which could further contribute to local economic diversification and job creation [69]. As a result, the development of floating OW has the potential to support a multi-use marine economy, integrating renewable energy, sustainable food production, and eco-tourism.

5 Conclusion

The main objective of this paper was to provide a comprehensive storyline of the sustainability impacts of OW and in more particular floating versus fixed technology. We identified several key takeaways. First, we identified that the impacts of a global uptake of offshore wind do not only happen where wind parks are built, but also where the materials and components come from, especially due to the mining activities and its consequential impacts. Second, this research shows the importance of taking a value chain perspective when assessing sustainability objectives, as several activities in the value chain are bottle necks when it comes to the sustainability performance. Examples are the energy mining during construction, the emissions of the materials and the maintenance emissions of especially floating offshore wind. Third, the end-of-life management of OW is one of the most important factors in the sustainability assessment of offshore wind, and although this is not reflected in the IO analysis, we accounted for this in the SDG interlinkages assessment, underlining the important of taking an integrated approach for sustainability assessment. Fourth, we have shown that OW generally contributes to greater value added through robust job creation along its entire value chain. In particular, floating OW shows significant promise for local job growth, offering a pathway to transform offshore O&G–dependent regions into renewable energy hubs. Last, while floating OW may offer local environmental benefits, such as reduced seabed disturbance, the broader global picture suggests that the material use – particularly in steel production – limits its overall environmental benefits. This underscores the need for a greener value chain, especially by reducing emissions from steel production and increasing the use of recycled and green steel or other more environmentally friendly materials.

This study faces several limitations. In this paper we focused on global, aggregated sustainability impacts of offshore wind deployment, rather than local or community-level effects. While issues of equity, justice, and the principle of “leaving no one behind” are central to the SDG framework, fully addressing these requires broader stakeholder involvement, particularly from the Global South, which was beyond the methodological scope of this paper. Our aim was to explore systemic and value chain-level effects based on currently available global data. Future research could complement this work through social Life Cycle Assessment (sLCA) and the SDG interlinkages approach used here could be adapted to support such more localized, equity-focused analyses. Additionally, this study does not model systemic feedbacks or non-linear interactions between SDGs. While the qualitative method helps identify emerging tensions, such as between economic growth (SDG 8) and environmental sustainability (SDG 13), a deeper exploration of these dynamics, including potential policy trade-offs and mitigation strategies, is left for future research. In addition, key factors such as circularity – specifically decommissioning impacts and the amount of recycled material content – are not captured in the IO data, despite their relevance to environmental impact assessments. Circular economy strategies in the OW sector are still underdeveloped [53], and including them in the IO analysis at this stage would introduce considerable uncertainty. Additionally, the IO model does not account for local variability, where environmental and marine impacts differ significantly depending on the wind farm’s specific location and scale. Qualitative data further introduces subjectivity from both respondents and researchers, and the literature review was not systematic, as this fell outside the study’s scope. Moreover, the analysis of floating OW technology is challenged by its relative immaturity; many assumptions regarding decommissioning, material extraction, and detailed effects like wake interactions remain invalidated, and differences in environmental impacts among various floating designs and material choices lead to additional uncertainties. The immaturity of the technology also leads to the main contribution of this paper: while floating offshore wind is not yet fully deployed, this research provides critical insights into how material choices and production processes affect sustainability outcomes. These findings offer valuable direction for future research aiming to make floating OW more sustainable when scaled up. More broadly, integrated assessments like the one presented in this paper should become a routine part of project planning for large-scale energy technologies. Quantifying impacts when the technology is deployed on large scale and using qualitative approaches to address the non-quantifiable aspects (e.g. circularity or life below water) provides a robust view of the sustainability impacts. This integrated approach allows for both a robust quantitative foundation and a deeper understanding of complex sustainability dynamics that underpin the deployment of technologies. Applying such approaches early in the conception and development stages, both locally and globally, can support more informed technology choices and help align innovation trajectories with long-term sustainability goals.

Supplementary Information
This is the link to the Supplementary Information

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6 Appendix A

Figure 4: The impacts of CAPEX of offshore wind on the SDGs across regions

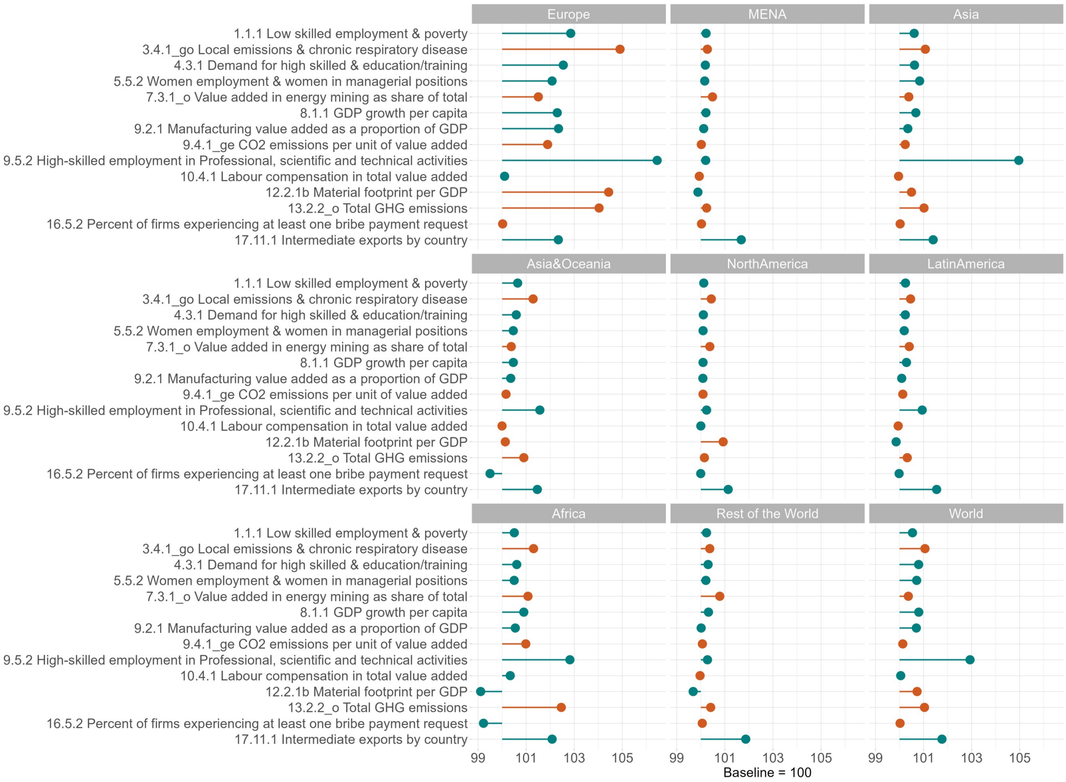

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Figure 5: The impacts of OPEX of offshore wind on the SDGs across regions