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Review article

Resilience of offshore renewable energy systems to extreme metocean conditions: A review

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ABSTRACT

The replacement of fossil fuels by intermittent renewable energy sources is transforming energy systems world-wide. A significant part of the future electricity demand will be supplied by offshore renewable energy, especially wind, but emerging technologies such as wave and tidal energy also offer great potential. However, the ability of offshore renewable energy systems – and of power systems and the societies that dependent on them – to cope with hazards such as extreme weather and metocean events is not well known. Resilience has become an increasingly important concept in the study of energy systems, as it addresses not only vulnerability to hazards but also the ability to recover from disturbances. Weather extremes are responsible for a majority of electricity blackouts, and the resilience of power systems to extreme weather hazards has long been an established field of research. However, the topic has not been examined to the same extent for offshore renewable energy systems; for marine energy technologies in particular, resilience is a novel concept. In the present study, we review the research that has been published starting from a discussion on the general resilience concept and its applicability for power systems. By identifying knowledge gaps and outlining directions for future research needed to build resilient and renewable energy systems, the paper contributes to several of the Sustainable Development Goals (SDGs). In particular, the paper supports the goals of *affordable and clean energy* (SDG 7), *climate action* (SDG 13), and *sustainable cities and communities* (SDG 11).

Contents

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1. Introduction

The share of renewable energy in the electrical grid is increasing at breathtaking speed. The International Energy Agency (IEA) predicts that global renewable capacity will increase by almost 75% (2400 GW) in the next five years [1], equalling the total installed power of China. A significant part of this capacity will be installed offshore: mostly as fixed offshore wind turbines, but also in emerging technologies such as floating offshore wind, wave, and tidal devices. It is predicted that annual offshore wind installations will increase 50% to over 30 GW in 2027, propelled by policy support in the European Union, the United States, and China [1].

A reliable supply of electricity is absolutely critical to the functioning of all modern societies. Every aspect of critical infrastructures, water and food supply, communication and information, finance, and transportation, depend on the grid [2]. Thus, threats to power systems are also threats to social stability, national security, and economic development. This dependence is increasing rapidly due to the ongoing electrification and digitalization of sectors throughout society. This interconnectedness also poses the risk that disturbances will lead to cross-sectoral cascading events with unfolding societal consequences.

These uncertainties and attend risks are increasing due to the growing penetration of intermittent renewable energy systems (RES) in the grid, adding to the complexity and interdependencies of the energy system. The capacity installed in wind farms is growing dramatically; 19 GW of new wind power capacity was installed in Europe in 2022, bringing the total to 225 GW, and 129 GW is expected to be installed in Europe between 2023 and 2027 [3]. A substantial part of new wind energy installations will be offshore [3]. The wind energy resource is more consistent and energetic in offshore regions than onshore, and the available land resources available for large onshore farms are becoming scarce. For instance, in its ambition to fully decarbonize electricity by 2030, the United Kingdom is expected to double onshore wind and quadruple offshore wind by 2030 [4]. In the United States, the goal is to install 20 GW of offshore wind by 2030 and 86 GW by 2050 [5], although recent changes in policy may put a halt to these ambitions. This increased penetration of intermittent energy sources is likely to reduce the resilience of the electric system to extreme events [6,7], by, for instance, reducing the balancing capacity of the grid to handle disturbances. The combination of the large expansion of offshore wind along the US Atlantic coast and the risk of hurricane conditions led Wiser et al. [8] to conclude that more research is needed to assess the risk posed by hurricane hazards to offshore wind.

In addition to these increasing complexities and dependencies, the threats posed to electricity systems are changing. Threats to energy and power systems have been categorized and compared in several comprehensive works [9–13]. Bompard et al. [9] divided them into natural (storms, earthquakes, lightning, space weather, etc.), accidental (equipment failures or operational faults), malicious (for criminal, military, or political purposes), and emerging. For the last category they identified systemic threats due to the increased penetration of intermittent RES and smart grids and the increasing interdependencies between critical infrastructures. Among 133 major blackouts that occurred around the world between 1965 and 2011, 63% were caused by natural hazards, especially storm events (54%) [9]. The second most common cause was accidents, which caused 31% of those blackouts. Jasiūnas et al. [13] state that extreme weather events are responsible for most of the disruptions in the energy supply, while rare extreme space weather events may represent the most catastrophic risk. Abedi et al. [12] classified risks to power system as natural hazards, intentional attacks, and random failures. They reported that the annual costs of weather-related blackouts in the United States ranges from 20 to 55 billion USD. The frequency of these events has increased over the last 30 years [14]. Since extreme weather is responsible for most of the disruption in the energy supply, and since their frequency, magnitude, and character are changing due to climate change [15], the risk to the future renewable energy system posed by extreme weather is significant if uncertain.

In light of ongoing changes in energy systems, societal interdependencies, and the threat landscape, traditional approaches to energy security or reliability are no longer sufficient. Emerging characteristics

Abbreviations

AC	alternating current	OWC	oscillating water column
CFD	computational fluid dynamics	OWSC	oscillating wave surge converter
DC	direct current	OWT	offshore wind turbine
EENS	expected energy not supplied	PA	point-absorber
EIU	energy index of unreliability	PV	photovoltaics
EVT	extreme value theory	RANS	Reynolds-averaged Navier–Stokes
FOWT	floating offshore wind turbine	RES	renewable energy systems
HILP	high-impact, low-probability	SAIDI	system average interruption duration
IEA	International Energy Agency	SAIFI	system average interruption frequency index
IPCC	International Panel on Climate Change	SDG	sustainable development goals
LES	large eddy simulation	WEC	wave energy converter
NREL	National Renewable Energy Lab	WEO	World Energy Outlook
O&M	operation and maintenance		

are increasingly difficult to predict [16], and emerging vulnerabilities and threats able to exploit existing vulnerabilities cannot always be foreseen. Instead of aiming to build failure-proof energy systems, many governments, utilities, and transmission system operators are aiming to build *resilient* energy systems that can cope with hazards and disturbances in a way that is safe for the society. Resilience to extreme weather hazards is an established concept in the context of energy systems in general and power systems in particular; it has been reviewed from various perspectives in a wide range of works [6,10,13,17–21]. But few scholars have examined the resilience of the changing power system in the light of the increasing penetration of RES. More specifically, there is as yet no review focusing on offshore RES, including established fixed offshore wind and emerging technologies such as floating offshore wind, wave, and tidal energy. Since the dependence on offshore RES is growing in power systems around the world, this poses an important knowledge gap.

The novelty of the present study is the contribution to close these knowledge gaps. The paper provides a thorough review of the existing literature, identifies knowledge gaps, and suggests directions for future research. Offshore RES have a potential of contributing to a sustainable and fossil-free energy system, needed to combat climate change. The paper aligns with the UN Sustainability Development Goals (SDGs) and Climate Change Framework in that it identifies needs for research needed to secure resilience of future energy systems with a larger dependence on offshore RES.

The remainder of the paper is structured as follows. In Section 2, the concept of resilience is reviewed. We discuss the term in relation to similar concepts, and offer our view on why resilience has enjoyed increased attention in the last decade. Section 3 deals with the hazard of focus in our study: extreme weather and metocean conditions, their quantification, and the expected impact of climate change on their frequency. A review of resilience in the context of power systems is provided in Section 4; this provides context and background for the review of resilience in offshore wind and marine energy systems in Sections 5 and 6, respectively. Based on the review and discussions in the earlier sections, knowledge gaps and directions for future research are identified in Section 7. The conclusions of the study are concisely summarized in Section 8.

2. The concept of resilience

2.1. Terminology

Definitions. The notion of resilience was first introduced in the context of ecology but has since been applied to areas as different as psychology, risk management, climate change impact, economics, and digital systems [19,20,22]. Generally, resilience means the ability of a system to "bounce back" after a disturbance. Whereas no universally accepted definition of resilience exists, the definition given by the IEA is well established for energy systems [23]:

> The capacity of the energy system and its components to cope with a hazardous event or trend, to respond in ways that maintain its essential functions, identity and structure as well as its capacity for adaptation, learning and transformation. It encompasses the following concepts: robustness, resourcefulness, recovery.

This definition includes some key terms, many of which have also been discussed, for example, by Heinimann and Hatfield [24] and Gasser et al. [20]. *Adaptation* refers to a system or behaviour changing in response to new or modified surroundings. Hughes [25] distinguishes adaptation from resilience in that a resilient system returns to its normal state after a disturbance, whereas adaptation changes the system into a new normal state. Other authors see adaptation as part of resilience, as in the definition by IEA, or do not even distinguish between the two concepts: Molyneaux et al. [17] identifies energy resilience as synonymous with adaptive capacity.

Transformation is the process of changing into something new. The energy system itself and the way that society uses the energy system are changing profoundly; the replacement of the vast majority of all energy sources by non-fossil, predominantly intermittent renewable energy sources, and the ongoing electrification of most sectors of society can be considered a transformation [26].

Robustness has been defined as the ability to withstand a given level of stress or demand without reducing system functionality, while *resourcefulness* is the capacity to identify problems, establish priorities, and mobilize resources when there are conditions that threaten to disrupt system functionality [27]. *Recovery* describes the property of re-establishing system functionality after it has been disrupted. It usually appears with the temporal measure *rapidity*, which indicates the pace at which recovery takes place. *Rebuilding* is a similar term that is often used synonymously with recovery. *Reconfigure*, or *build back better*, are related terms that describe the aim to make a system fault-tolerant or improved after it has been recovered [28]. The ability to reconfigure a system such that its future resilience increases is connected to the *learning* ability of the system and is included in the IEA definition of resilience quoted above. Another property of resilient systems that is often mentioned (but is not in the IEA definition), is *redundancy*, which refers to the extent to which components of a system are substitutable without loss of functionality. This is sometimes expressed as the *functional diversity* or *modularity* of a system.

As introduced by Bruneau et al. [27], resilience is often described using the *resilience curve* (see Fig. 1), with a multitude of variations of this original conceptualization existing [22]. The resilience curve shows system performance as a function of time: before, during, and after a major disruption. Expressed differently, the four stages of resilience can be defined as planning, absorption/disruption, recovery/restoration, and adaptation. In a more general categorization, the resilience curve during an event can be divided into two main parts: the absorption (or disruption, or draw-down) phase and the recovery (draw-up) phase. The system functionality is described by the graph. In the context of energy systems, system functionality is usually related to the continuous supply of energy to the society.

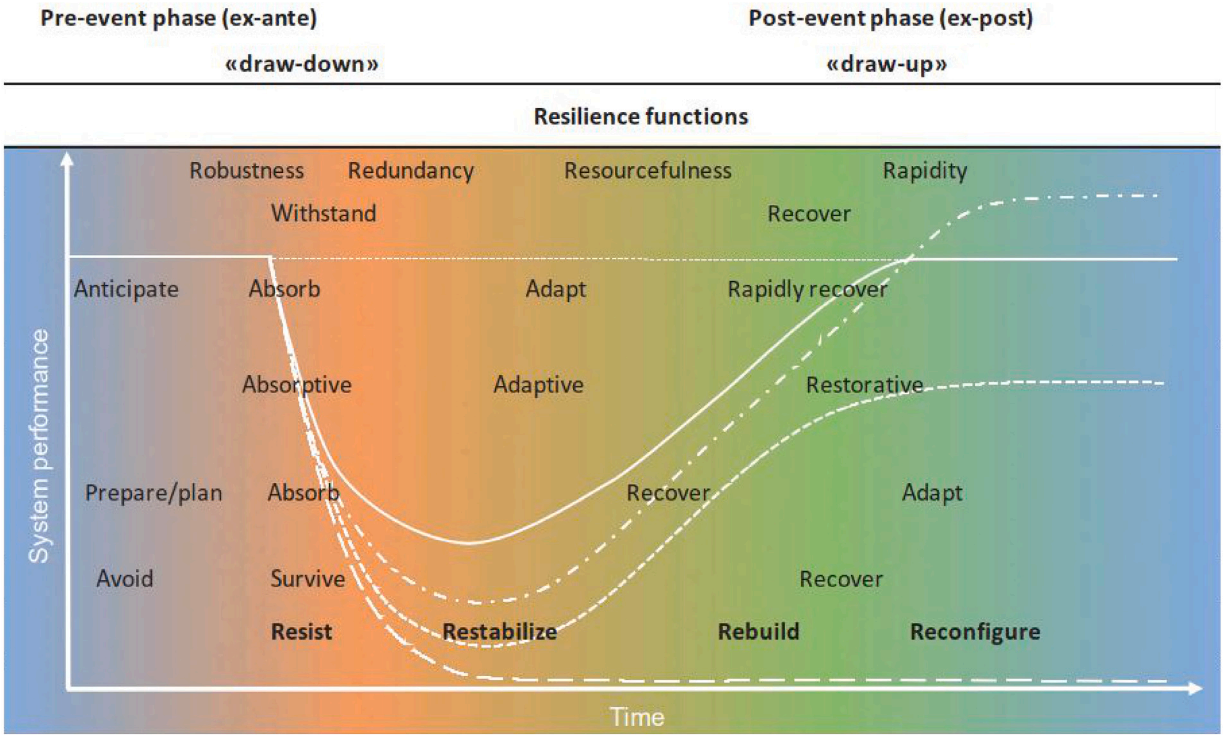

Fig. 1. Resilience is often described in terms of the resilience curve, showing the system functionality before, during, and after a disturbance as a function of time. The resilience curve during an event can be divided into the "draw-down", or absorption phase, and the "draw-up", or restoration phase.
Source: The figure is adapted from Gasser et al. [20] and shows where different resilience functions come into play in the resilience process.

Resilience metrics. The properties of the resilience curve in Fig. 1 can be used as indicators of the resilience of a system to a given disturbance, whether actual or simulated. Time-dependent functions can be defined for the system performance and evaluated in different scenarios; for examples, see [22,29,30]. The vertical reduction in system functionality following a disruption can be used as a measure for system vulnerability or system robustness. The integral of the resilience curve measures the amount of system functionality, represented by $F(t)$, that was not provided over a certain period of time $[t_0, t_1]$ [27],

$$R = \int_{t_0}^{t_1} (1 - F(t))\, dt, \tag{1}$$

such as energy not supplied if the system functionality describes an energy supply. Many resilience metrics can also be connected to economic dimensions [31], such as the cost of repair or redundancy functions. Roege et al. [32] provide a comprehensive list of energy resilience metrics and measures, separated over four stages of resilience: plan, absorb, recover and adapt, and over four dimensions of decision-making: physical, information, cognitive, and social.

Resilience measures. Measures to improve resilience aim to make a system meet all the criteria to be called resilient; that is, robustness, resourcefulness, ability to recover rapidly, functional diversity, and so on. Gasser et al. [20] have pointed out that resilience management always aim to minimize the potential consequences resulting from a disruptive event and to recover efficiently from a potential system performance loss. Resilience measures usually depend on context and time. For example, the recovery of a power system after a major storm may depend on reserve energy capabilities, power system topology, availability of personnel and spare parts, weather conditions, prioritization schemes, etc. Measures to increase resilience to some threats may actually reduce resilience to other threats [13], and no resilience measure will fit all situations [32]. For example, burying transmission cables underground will make a power system more robust to storms but might create new vulnerabilities to earthquakes or floods.

2.2. Related concepts

Resilience is related to several other concepts describing the ability of a system to cope with stress or hazards, such as energy security, reliability, robustness, vulnerability, sustainability, and risk. The overlaps and distinguishing features of these related concepts will now be discussed.

Energy security initially referred to maintaining an uninterrupted supply of oil in the United States and other developed countries at an affordable price. It has since been given a broader meaning, and a variety of definitions exist [33], but mostly boil down to an energy system's ability to supply energy to meet demand at an affordable price [17]. The IEA defines energy security as "reliable, affordable access to all fuels and energy sources", thus focusing on the energy sources rather than the energy system at large. Jasiūnas et al. [13] argue that energy security encompasses resilience and that the two terms can be used interchangeably, except for explicit references to resilience contexts such as rebounding from extreme or unexpected impacts. Jesse et al. [19], on the other hand, report that energy resilience can be seen as an extension of energy security, which is in line with the view in this paper. Energy security is often described as including the elements of availability, accessibility, acceptability, affordability, and diversification [17].

Energy reliability is distinguished from resilience in that the former concept considers the intended function under specified conditions with a focus on high-probability, low-impact risks (*e.g.*, failures in power systems due to fatigue in components), whereas resilience focuses on high-impact, low-probability (HILP) risks, such as major blackouts following an earthquake [34]. Chi et al. [35] compared the assessment of reliability and resilience for power systems and concluded that conventionally used reliability indices (*e.g.*, the system average interruption frequency index) are insufficient to describe the non-stationary faults and restoration processes entailed after a major disruption. They also point out that reliability analyses often have access to extensive historical data, whereas there is little data available for resilience studies, due to the low-probability nature of these events. The time dimension of restoration in reliability assessments is generally restricted to known and manageable system failures while for resilience analyse relates to previously unprecedented modes of failures requiring explicit consideration of restoration processes.

Robustness is included as a component of resilience in the IEA definition. It is defined as the ability to withstand a given level of stress or demand without reducing system functionality. As such, it is connected to a system's ability to absorb the impacts of a disruption. A concept that can be viewed as a synonym to robustness is *resistance*, which is defined as the ability of systems to remain within an acceptable range of functionality [24]. Robustness can be regarded as embedded in the system design, whereas resilience covers both system design and operational aspects. *Stability* refers to the ability of a system to withstand disturbances; a system is said to be stable if small perturbations result in a new solution that is close to the original one. Although this resembles the definition of robustness, Jen [36] argues that the two concepts differ in that robustness describes persistence in systems for which we do not have the mathematical tools to use the approaches of stability theory and that robustness requires studying the coupling of dynamics with organizational architecture and using implicit rather than explicit assumptions about the environment.

Vulnerability stems from the Latin word vulnare (to wound), and can be defined as the degree to which a system is sensitive to disruptions. As such, it can be regarded as the antonym of robustness [37]. A system that is vulnerable to a disruptive event loses (part of) its system functionality. In the resilience curve, this amounts to the performance drop after the disruption. Reducing vulnerability thus reduces the impact of a disruption and increases resilience.

Sustainability is a broad term with several definitions, often related to environment. The review by Marchese et al. [38] shows that resilience is sometimes viewed as a component of sustainability, but sometimes the relationship is the other way around, or regarded as two separate concepts. One important difference between the two are their temporal scales: resilience covers the time immediately before, during, and after disturbances, whereas sustainability covers much longer time scales, often several generations [38].

Risk for engineering systems is often viewed as the probability of an undesired event and the related losses [39]. Risk assessments link identification of hazards and their consequences with the probability of occurrence, and usually result in measures to reduce the frequency or impact of hazardous events. They differ from resilience assessments, similar to reliability assessments, in that they tend to have a hazard driven focus rather than a vulnerability and recovery perspective of high-impact low-probability events [40]. The planning stage of resilience assessments often includes traditional risk analysis.

2.3. Why resilience

The energy system is undergoing major transformations, driven by the replacement of fossil fuels by intermittent renewable energy sources, and the electrification and digitalization of all sectors in society. To foresee how this will affect its resilience to emerging threats is not a simple task. Even the most renowned experts in the energy sector have difficulties making accurate projections regarding its future. The World Energy Outlook (WEO), released annually by the IEA, has notoriously underestimated the future installations of renewable energy technologies [41]. The 180 PW installed solar PV projected by the 2010 WEO to be reached in 2024, was achieved in January 2015, and the 2002 WEO projections for wind energy in 2030 were exceeded by 2010. Even if these erroneous predictions can be partly explained from the conservative approach used by the IEA to assume implementation of future policies [42], they still highlight an obvious fact: the future is unknown, sometimes profoundly so. This is in particularly true when considering complex systems undergoing vast transformations, like electrification and digitalization of many societal sectors, and climate change, where the uncertainties are on an epic scale. Since the threats and vulnerabilities are unknown and may be increasing, it is not feasible to plan for protection of energy systems to withstand any kind of disturbance. In addition, the complexities and interdependencies introduced by the ongoing transformations in the energy systems may make the societal impact of disturbances more severe, and increase the risk of cascading failures. It is reasonable to aim for resilient energy systems that are able to cope with and bounce back from (unknown) disturbances.

3. Extreme weather and metocean conditions

The majority of disruptions in the power system are caused by extreme weather, mostly storms [10], thus we here focus on the resilience of energy system to extreme weather hazards. A large part of the costs in offshore renewable energy project can be associated with operations and maintenance activities [43], which to a high degree are weather dependent [44]. In this section, extreme weather and metocean scenarios of relevance for energy systems are reviewed.

3.1. Extreme weather as a direct and indirect threat to energy systems

The impact of blackouts caused by weather extremes in the United States cost 20–55 billion USD every year [45], and the frequency of blackouts appears to be increasing [46]. Harsh weather conditions were reported to cause 33% of the blackouts in Canada [47] and around 45% of the line failures in Turkey [48]. A long list of power outages caused by extreme weather were listed by Wang et al. [21]. Due to their higher occurrence and larger number of affected people, wind storms, ice storms, and thunderstorms are viewed as posing more severe risks to power systems than wildfire and high temperatures [21].

Even if storms are the main cause of failures in power systems, other extreme weather conditions may put direct or indirect pressure on energy systems. Excessive snowfall can cause failures of overhead power lines, icing can be destructive to wind turbine blades, severe ice conditions can damage infrastructures of various kinds, and cold waves can cause indirect pressure through increased energy demand; for example during the 2001 Texas cold wave, the temperature was 10 °C below average, and demand increased to an extreme peak of 69 GW [21]. Heat waves also cause increased energy demand due to air condition usage (a temperature increase of 1 °C may cause a 3%–7% increase in demand [49]) and thus affect transmission and distribution transfer capability. Heat waves can also affect the cooling capabilities of power plants: there have been occasions when nuclear power plants in Europe have had to close down due to the increase in temperature in river water [12]. Droughts affect river run-off, leading to reduced hydropower capacity. Rain and floods may be hazardous for substations, switchgear, or other facilities on the ground.

Several of these conditions are particularly hazardous in power systems with a large penetration of offshore RES. In many countries, hydropower is used as a regulating capacity. Combinations of heat waves and droughts can overwhelm these regulating capabilities, especially if nuclear power plants have reduced capacity at the same time. In addition, most renewable energy technologies are by definition dependent on the weather. A grid largely dependent on wind energy is vulnerable to extensive periods without wind, know as wind droughts, or of wind above the cut-off threshold at which the wind turbines are shut down.

In offshore conditions, several types of environmental extremes challenge the operation of wind turbines and wave generators. These include extreme wind and wave conditions, icing on blades, precipitation at relatively strong winds, and ice in the water. Fast or floating ice should be considered at higher latitudes because it can cause severe damage to infrastructures [50,51]. Icing of wind turbines has mainly been investigated in mountain regions and at high latitudes [52–54]. Due to the fact that very few offshore wind farm projects exist in cold climate, the role of icing on blades is not fully understood, and it is probable that sea spray exacerbates icing [55].

3.2. Quantification and prediction of extreme metocean conditions

The "extreme" in *extreme weather conditions* can relate either to the weather characteristics being extreme in terms of their probability of occurring at the specific site, or to the impact on a given system being extreme. The latter can be quantified in terms of reduced performance, such as the number of affected customers or disconnected load, or in terms of the severity of the failures. Offshore wind turbines (OWTs) subjected to hurricane conditions are exposed simultaneously to turbulent wind loads and irregular wave loads. According to the IEC Standard 61400-3, the peak period of the sea state should be assumed as normally distributed and conditioned on the wave intensity [56]. Beyond the magnitude of extremes, other relevant aspects from an impact perspective include the duration, the spatial area affected, timing, frequency, onset date, and continuity (that is, whether there are "breaks" within a given spell).

The main challenge in quantifying extreme weather parameters is scarcity of data. At most measurement stations, recorded data exist for between 20 to 50 years though some stations have records that date back up to 150 years. Extrapolating the recorded data to return periods of 1'000 or 10'000 brings with it large uncertainties. As a complement, stochastic catalogues of 100'000-return period events have been simulated [57,58] and can be combined with wave and wind models to obtain weather hazard parameters [59]. To reduce complexity and computational cost, a simpler approach using a parametric model was introduced by Hallowell et al. [60]. With the objective of reducing uncertainty in hazard prediction for OWT reliability, Qiao et al. [61] compared three metocean models and validated one of them with data measured from 23 storms and with hindcast data from WaveWatch III. They found that a metocean model that considers the Holland model within the hurricane and wind–free conditions surrounding the hurricane for its meteorological forcing, can be effective in assessing hurricane risk.

Indices describing extremes often reflect relatively moderate extremes, such as events occurring 5% or 10% of the time. For rarer extremes, extreme value theory (EVT) is used. EVT aims at deriving a probability distribution of events from the upper or lower tail of a probability distribution (typically occurring less frequently than once per period of interest) [62]. Other approaches used for evaluating characteristics of extremes or changes in extremes include analysing trends in recorded events and investigating whether records in observed time series are being set more or less frequently than would be expected in an unperturbed climate [63–67]. To predict combined extreme metocean conditions, *e.g.*, characterized by both wave height and wind speed, joint probabilistic distributions of the involved parameters are needed. These are often defined in terms of an environmental contour, as displayed in Fig. 2. The traditional approach for creating environmental contours uses the inverse first-order reliability method (I-FORM) [68]. However, due to the scarcity of data in the tails of the probability distributions and unknown dependencies between the environmental variables, establishing environmental contours is equipped with large uncertainties [69,70], and environmental contours created by different methods often predict significantly different scenarios [71–73].

The uncertainty of reliable statistics and representation of extreme metocean scenarios is further amplified by changes in weather patterns caused by climate change. Generally, it is not expected that climate change will lead to increases in extreme wind speeds, but changes in wind patterns might trigger increased or decreased extreme wind conditions in specific regions [51,74,75]. One of the most severe weather phenomena for offshore conditions are tropical cyclones. The total energy of tropical cyclones is not expected to increase due to the warming climate, but the most intense tropical cyclones and also mid-latitude storms could be slightly more extreme in a changing climate, as assessed with a medium level of confidence by the International Panel on Climate Change [74]. An example of how climate change can affect the European electricity system is the likely increased frequency of heat waves and droughts, which will reduce the cooling capacity of nuclear and fossil fuel plants [76]. In recent decades, many nuclear power plants in Europe have been obliged to reduce their production because of limited access to cooling water during hot summers [77]. Van Vliet et al. [78] demonstrated that changes in water resources due to climate change could imply reductions in useable capacity for 61%–74% of the hydropower plants and 81%–86% of thermoelectric power plants worldwide between 2040 and 2069. It is not unlikely that reduced balancing capabilities in the grid would occur simultaneously as low wind production capacity due to poor wind conditions and high demand due to extensive use of air-conditioning; the combination will put extraordinary stress on the electricity system [76,79] and may thereby implicitly affect the offshore renewable energy systems. The combination of processes (climate drivers and hazards) leading to a significant impact is referred to as a *compound event* [80], and need to be carefully evaluated to understand the changes to stresses on the energy system in a changing climate. For Nordic conditions, it is likely that a warmer climate increases the accessibility for operation and maintenance (O&M) as well as some stress on offshore installations will be reduced due to reduced ice conditions [44]. One consequence of climate change is a tendency of increased persistence in weather patterns [81], which will have implications for various aspects of the compound events and extreme conditions of relevance for offshore systems.

4. Resilience of power systems to weather extremes

Weather extremes are responsible for a majority of the blackouts. As examples, the Hurricane Sandy caused power outages for millions of people in the USA in 2012, and the snow storm in southern China in 2008 led to blackouts for 15 million households [82]. The resilience of power systems to extreme weather events has been studied extensively [21]. The brief review that is provided in this section serves as a context and introduction of established methods that will then be studied for offshore renewable energy systems in Sections 5–6.

4.1. Power system transformations

A continuous supply of electricity is critical to the functioning of all modern societies. All critical infrastructures, the industry, and our everyday lives are heavily dependent on the reliability and resilience of the electric grid. This dependency is currently increasing immensely due to the ongoing *electrification* throughout society, in particular the transport and industrialization sectors. The role of electrification on energy resilience is disputed. As discussed above, redundancy and functional diversity are general traits of resilient systems. In the case of the energy system this can mean, for instance, dependency on not a single energy source or energy transmission and distribution path, but a range of sources and paths, such as natural gas and redundant transmission and distribution lines. However, if this functional diversity is also dependent on the electric grid, such as the pumping of natural gas, the diversity is lost during blackouts. Alongside with the ongoing electrification, *digitalization* is implemented in all critical infrastructures. The implementation of smart grid functionalities in the power system enables increased monitoring and control capabilities, which can be used as measures to increase the resilience to extreme weather threats, but can also introduce new threats [83]. To cover the increasing electricity needs while not jeopardizing climate and environmental goals, *renewable energy technologies*, mostly of intermittent nature, are installed at a rapid speed.

These three ongoing transformations of the power system – electrification, digitalization, and increasing penetration of intermittent renewable energy sources – add complexity and uncertainties to the system. These changes are important to understand and accommodate for when studying the resilience of the power system to existing and emerging threats.

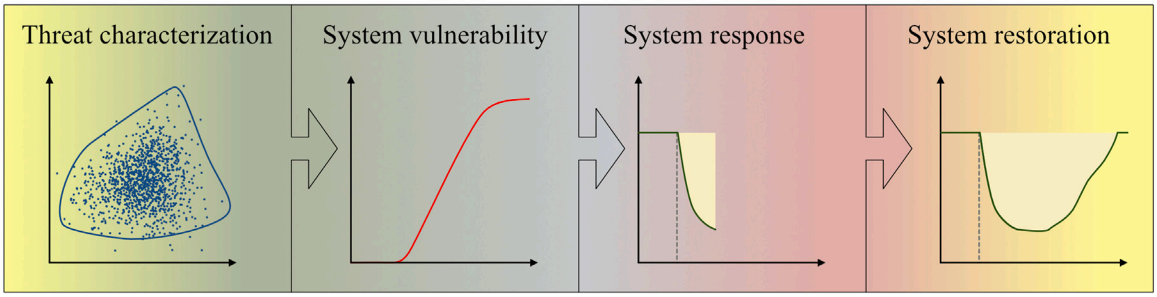

Fig. 2. Resilience assessment includes assessing the threat characterization, vulnerability of the system to the threat, the system response, and the system restoration. The threat characterization is illustrated by an environmental contour and shows the expected 50-year combination of extreme wind speed and wave height, for instance. The system vulnerability is illustrated by a fragility curve which designates the probability of failure as function of the environmental load. The system response and system restoration show how the system functionality is reduced and restored during the absorption and restoration phases following the disturbance.

4.2. Power system resilience metrics and assessments

Panteli and Mancarella [34] described resilience of power systems as the ability to "anticipate extraordinary and high-impact, low-probability events, rapidly recover from these disruptive events, and absorbing lessons for adapting its operation and structure for preventing or mitigating the impact of similar events in the future". Other organizations worldwide, such as the IEEE Task Force on Resilience [84], attempted to define, quantify and enhance the concept recently. The electric grid is designed based on the $N-k$ security principle, stating that if k components should fail, the network should remain operational. In recent years, several extreme or unexpected events have caused large disturbances in electric grids around the world, showing that the $N-k$ principle is not sufficient to guarantee a secure energy supply [82]. This extended security perspective can be viewed as a systematic vulnerability assessment of the inability of a system to withstand strains and the effects of failures [40]. As both the power system and the societal dependencies on electricity are undergoing transformations, new vulnerabilities are emerging that can be exploited by existing or emerging natural or man-made threats. Disruptions can be expected in the future, and their impact could be catastrophic. Resilience has therefore gained increasing attention in the context of power and other key systems; Jesse et al. [19] report that the number of publications on resilience have increased by roughly 1600% over a 15 year period.

Comprehensive frameworks and methodologies for assessing the resilience has been presented by many authors and both qualitative and quantitative methods are utilized. Bie et al. [82] categorize the quantitative assessment methods as simulation based, analytical, and statistical based on historical data, among which simulation based models are dominating. Different methods may be needed to evaluate resilience during different phases of resilience; the vulnerability, for instance, must to be assessed for the absorption phase and the rapidity of repair operations for the restoration phase. Espinoza et al. [31] structured the analysis into four phases: threat characterization, vulnerability assessment of the system's components, system reaction, and system restoration, illustrated in Fig. 2. The method was applied to a test case of the UK grid, subject to storms and floods. The vulnerability assessment was based on fragility curves of power lines and towers to the two weather hazards, and assumptions for mean time to repair were made for lines and towers to model the power system restoration. A review of different approaches to assess the vulnerability of electric grids was provided by Abedi et al. [12]. The available methods were categorized into topological, logical, functional, and flow methods. The different approaches emphasize different aspects of the grid, and the appropriate model depends on the type of event and specific case under consideration. Sperstad et al. [85] suggested a "bow tie model" for assessing the vulnerability of power systems, and connected it to the general resilience engineering terminology as shown in Fig. 3. Dunn et al. [86] computed fragility curves for electrical overhead lines as function of wind speed based on data on 12'000 failures in the UK power system, and concluded that a precise spatial information is required to avoid underestimating the fragility of the infrastructure components. A similar approach was taken by Kiel and Kjølle [87,88], who developed a spatio-temporal model for failure probability of transmission lines as function of wind speed, based on historical failure data for the Norwegian power system. By utilizing the method, they found that the expected annual energy not supplied was found to be significantly larger than estimated using traditional reliability analysis.

A majority of works on power system resilience has been focused on the vulnerability to hazards, or the disruption phase of events. Landegren et al. [89] focused on the restoration phase, and studied the sensitivity of electricity networks as a function of repair system resources. The three resilience metrics robustness, rapidity and resilience loss were quantified in a Swedish electricity network in [90]. Using a hybrid model composed of a graph theory model for representing the grid and a queueing model for the repair operations, extreme scenarios could be identified where the robustness and rapidity were poor.

If the system performance level in the resilience curve in Fig. 1 describes the supplied load in a power system, the area above the curve gives the expected energy not supplied (EENS), measured in MWh. A related quantity is the energy index of unreliability (EIU), defined as the ratio between the EENS and the total energy demand in the system. The drop in system performance is determined by the fragility, or vulnerability, of the system, the time after the disruption. In addition to those, economical aspects (restoration cost, cost implications of energy not supplied), time aspects (blackout duration, time to restoration), operational aspects (available reserves, trained personnel), and societal aspects can be used as metrics to evaluate the resilience of power systems. There are hence overlaps between the engineering conceptualization of resilience and reliability, but where the former focus on the vulnerability and recovery of the power system towards unexpected or extraordinary events and systemic aspects [34,40].

Traditionally, cost optimization has been an integrated part of reliability assessments of power systems; in particular asset management has aimed to maximize the long-term profits of electricity market actors while continuously delivering a high service to the costumers [91]. Several risk assessment and maintenance strategies have been developed to reduce capital and operational costs while ensuring high reliability.

Resilience metrics (expected energy not supplied, conditional value at risk) as well as standard reliability indices (system average interruption duration/frequency index (SAIDI/SAIFI)) were studied and compared by Li et al. [92] for two island off-grid power systems with energy supplied by solar PV and heat power plants, subject to storms. They showed that the PV system had lower costs and higher reliability under normal conditions, but that the heat power plant system showed lower risk during the extreme event. There is also a trend in using and applying risk-based metrics, such as (conditional) value at risk, in resilience quantification and enhancement to better reflect and explicitly consider tail risks to power systems [93,94].

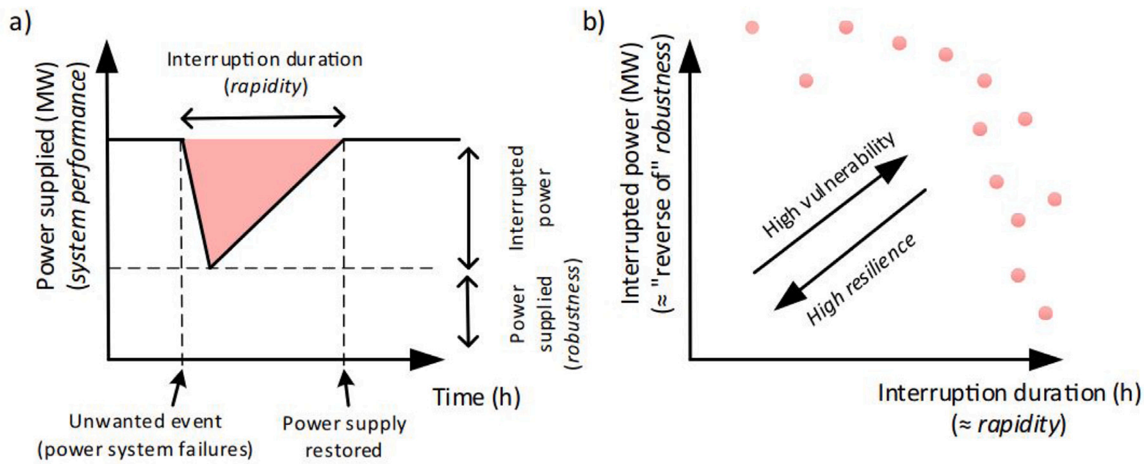

Fig. 3. (a) System performance (power supplied) of a power system as a function of time during a disruptive event. (b) Relationship between vulnerability, robustness and resilience for power systems as function of the interruption duration in the power supply.
Source: Figure adapted from Sperstad et al. [85].

Large blackouts are often caused by cascading failures in power systems. An initial disturbance can trigger the sequential failure of other subsystems [95]. An analysis of the chain of events in 31 historical large blackouts was carried out by Huang et al. [96], who found that generators and transmission lines were the most vulnerable entities in the studied cases. Cascading failures in power grids have been studied using a range of methods [97], including agent based models [98], complex network models [99–103], DC power flow models [104,105], AC power flow models [106], or combinations of models [107]. Multi-layered complex network models combined with deep learning tools can be particularly useful for modelling the operational resilience of modern grids, including interdependencies with communication or other systems [6]. Further, different cascading analysis models have been developed specifically designed for power systems resilience quantification, including [108–111].

4.3. Measures to improve resilience of power systems

To improve resilience of power systems, the different approaches can be categorized as increasing robustness, reducing impact, and improving recovery [112]. Panteli and Mancarella [14,34] reviewed the current literature and concepts, and compared measures to increase the resilience. They distinguished between "hard" measures, intended to reduce the vulnerability of the grid to severe events , and "soft" measures, intended to increase the operational capabilities of the grid to more efficiently adapt to disturbances. This also falls within the resilience trilemma, that is making the infrastructure stronger (more robust), bigger (more redundant) or flexible (more responsive) to the event. Hard measures is the more traditional approach to increase the robustness of power systems, and include strategies such as undergrounding transmission or distribution lines, rerouting grid to areas less prone to hazards, upgrading poles to more robust materials, elevating substations, and managing vegetation around overhead power lines. Soft measures, such as increased monitoring and control, can also provide means of increasing the robustness, by fast detection of potential hazards and advanced demand side management and protection schemes to prevent power outages and cascading failures. Panteli and Mancarella [34] argued that reinforcing the network is always equipped with large costs, but may not always have the desired effect, and that a hybrid network with synergies between hard and soft measures was optimal to achieve a good trade-off between resilience and cost efficiency. Arghandeh et al. [18] pointed out that a 90% of customer outages in the USA are related to distribution network failures, but that the majority of studies have focused on resilience in transmission systems.

The impact of disturbances can be reduced by improving the resourcefulness and redundancy of the power system. This includes distributed power generation or storage facilities (back-up generators and batteries), improved demand response management, load shedding, and islanding to prevent cascading events. Microgrids can be used to provide electricity to critical services during power outages, and were proven useful during the Hurricane Sandy as well as during the Great East Japan Earthquake [82]. Smart grid technologies can also be used to improve monitoring and control to enable fast localization of power outages and load balancing or rerouting.

Rapid restoration following disruptions is part of the definition for resilient systems. This has been studied in the context of power systems in a number of works [113–119]. To improve the recovery after a disturbance, reconfiguration has traditionally been the main means to restore supply immediate after a disturbance [82].

5. Resilience of offshore wind systems to extreme weather

As reviewed in Section 4, power system resilience to extreme weather is an established research topic since at least the last decade. Some of the methods and approaches have been applied to offshore wind energy systems, which will be reviewed in this section. After a background on the status of offshore wind technologies in Section 5.1, the resilience concept applied for offshore wind energy systems and the dependent electric grid will be discussed in Sections 5.2–5.3.

5.1. Offshore wind technologies and installations

Since the first offshore wind farm was installed in Denmark in 1991, OWTs have reached a widespread commercialization, and are being installed at a rapid speed around the world today. In 2020, there were 112 offshore wind farms in operation, with a total capacity of 18.9 GW [120]. Only the year after, the total capacity exceeded 50 GW [121]. China was responsible for most of the installations in 2021 (13.8 GW), followed by the UK (1.9 GW), Vietnam (643 MW), and Denmark (604 MW) [121].

Not only the number of offshore wind farms have increased; also the size of the turbines are increasing. In Europe, the average wind turbine size was 3.2 MW in 2010, while it was almost doubled reaching at 5.9 MW in 2017 [122], 7.6 MW in 2020 [121], and current OWTs having a capacity of 10 MW, projected to reach 15 MW by 2027 [121]. To share infrastructure and operational costs, the OWT are installed in farms, with trends to increase the total farm capacity. Of the installed capacity in Europe in 2019, 89% corresponded to farms with rated power above 150 MW [123].

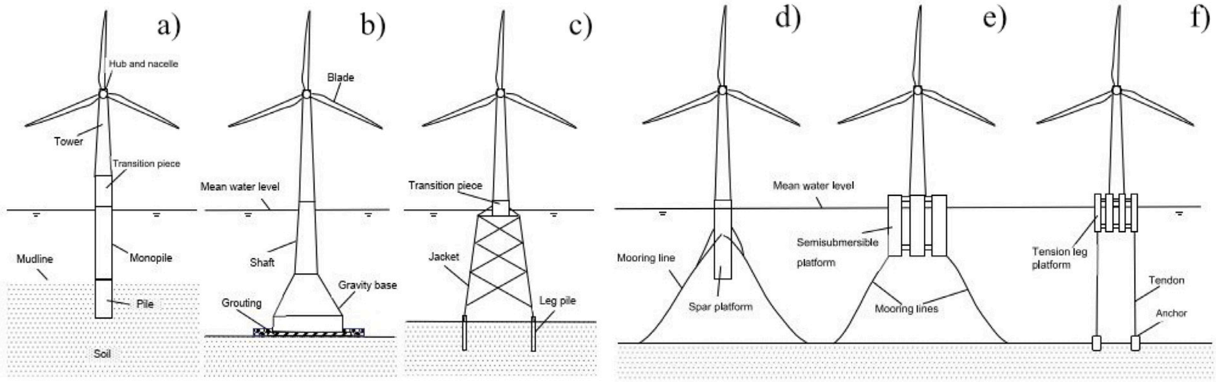

Fig. 4. Different offshore wind technologies. (a–c) monopile, gravity-based, and jacket foundations are common technologies for bottom-fixed OWT. (d–f) Floating spar platforms, semi-submersible platforms, and tension leg platforms are examples of floating OWT technologies.
Source: Figures from Jiang [124].

The vast majority of offshore wind installations are bottom-fixed and based on established onshore wind technologies. Common ones include monopile foundations, gravity-based, and jacket foundations, shown in Fig. 4. Monopiles are designed for water depths up to 40 m and is the most commonly used technology. 63% of the operative offshore wind farms in 2018 adopted a monopile foundation; in America in 100% of the cases, whereas 70% in Europe and 43% in Asia [120]. Jacket foundations allow installations at somewhat larger depths, around 50–70 m, and make out 7% of the installations. Gravity based foundations are usually constructed out of concrete and have been adopted mainly in offshore wind farms in Asia. Other bottom-fixed foundations include tripods, suction buckets, and high rise pile cap foundations [120].

For installations in deep water, the bottom-fixed structures are not feasible, and floating wind energy technologies are emerging, but have not yet reached the same technical maturity as fixed turbines. Three examples are shown in Fig. 4 and include floating spar, semi-submersible, and tension leg platforms. The first floating wind farm was the Hywind Scotland, installed in 2017 as a pilot park of 30 MW by Equinor in Scotland [120]. As of 2021, the total capacity of floating offshore wind reached 123.4 MW [121].

5.2. *Resilience of offshore wind systems to metocean conditions*

As discussed previously, the resilience time frame can broadly be divided into the absorption and restoration phases. These will be studied separately in Sections 5.2.1 and 5.2.2, after which resilience of offshore wind systems will be discussed more comprehensively in Section 5.2.3.

5.2.1. *Absorption phase*

The ability of a system to absorb a hazardous event without losing its system functionality is determined by its robustness to the hazard. Much work to assess the robustness or vulnerability of wind energy systems to weather hazards has been carried out. The vulnerability can be separated into explicit vulnerability due to failures of wind turbine components during extreme weather loads, and implicit vulnerability due to ramp-down of the wind turbines at wind speeds above the cut-off threshold. Implicit vulnerabilities also include hazards inherent in the power system, such as overloads failures. The implicit vulnerability will be handled separately in Section 5.3, and here the focus is on the explicit vulnerability.

In general, the external loading on a structure can be separated into two classes that need to be treated differently: fatigue, and ultimate loads. Fatigue failures are results of wear due to repeated cycles of long-term operation in normal conditions, whereas ultimate conditions are single loads above the design criteria of the structure, often occurring due to extreme weather scenarios.

Even if offshore wind technology is based on established onshore technology, its vulnerability to extreme weather conditions is expected to be higher than onshore wind [125,126]. Several authors have pointed out the risk related to hurricane impact on wind turbines. Rose et al. [127] studied wind farms in Texas, USA under hurricane risk and concluded that 10% of the offshore wind power could be offline because of hurricane damage with a 100-year return period, and 6% for a 10-year return period. Simulations carried out by Worsnop et al. [128] revealed that wind turbines subject to a category 5 hurricane would encounter conditions outside of the design standards, with expected structural damage as a result. Kim and Manuel [129] showed that hurricane-induced loads could cause the bending moment of the tower to increase by a factor of three. A difference between onshore and offshore wind turbines, is the obvious fact that OWT are subject to simultaneous loads arising from wind, waves, and currents, and responses to multivariate extreme conditions such as described by the environmental contours in Section 3 must be analysed. Fragility curves of OWT structures have been derived as functions of combination of extreme wind speed and wave height conditions by several authors [130–134]. An example by Pokhrel and Seo [132] can be seen in Fig. 5; the fragility curve shows the exceeding probability of the overturning bending moment of the OWT tower at mudline as a function of wave height. The same 5 MW OWT monopile, developed by NREL, was studied using the FAST/OpenFAST software by several groups, see [134,135]. By developing statistical regression models to connect the critical responses of the OWT to the input wave- and wind parameters, it was shown that the wind-sensitive blade tip deflection resulted in the fragility of 99% at critical wind speed of 75 m/s and a wave height of 20 m [134]. Another approach was taken by Kim and Lee [136]. Under the assumption that the dynamical response of the OWT jacket support structure is proportional to the statical, they computed the reliability index of the horizontal displacement of the structure subject to wind and wave loading. Hashemi et al. [135] concluded that variations in the input wind and wave data give rise to large differences in the structural response, resulting in a high degree of uncertainty in the results. Resonances or complex dynamics of OWTs in certain conditions may imply extreme loads or damages also during operational wind speeds [137], or during unforeseen combinations of wind, wave, current, and geotechnical conditions [138,139]. This complicates the prediction of the systems' robustness in the offshore environment. Several approaches to addressing this issue exist, such as evaluating responses in a larger set of conditions than along the environmental contour (including accurate coupling of wind-wave–current-geotechnical loads), defining extended environmental contours that include more variables [138], or evaluating more modes of operation outside of parked conditions [133,140]. Haselsteiner et al. [141] pointed out that short-term variability in the response constitutes an

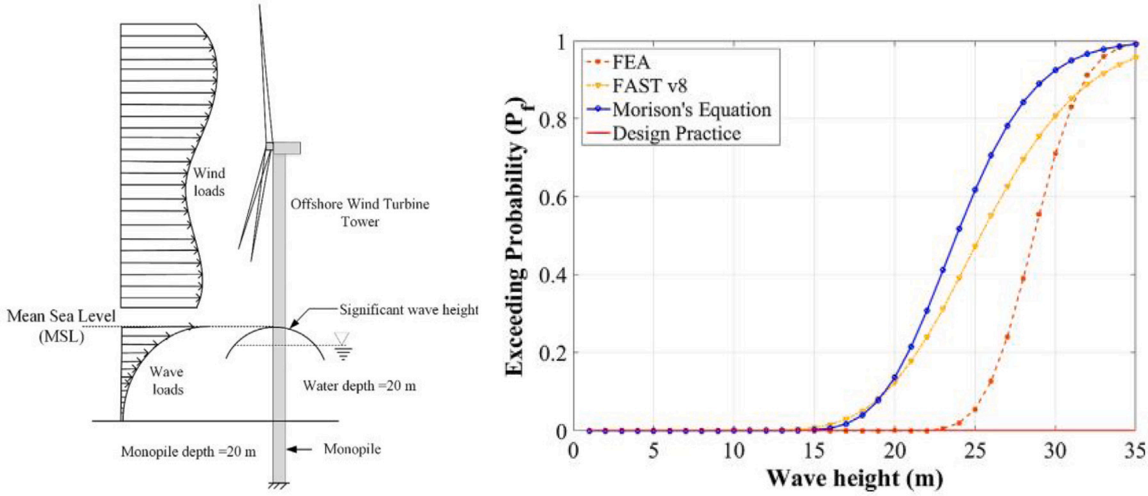

Fig. 5. *Left:* Schematic of the NREL offshore 5 MW baseline wind turbine, developed by NREL [142] under distributed wind and wave loads. *Right:* Fragility curve of the overturning bending moment of the monopile tower at the mudline, as function of the wave height and using different numerical approaches.
Source: Both figures from Pokhrel and Seo [132].

even larger source of uncertainty than the contour itself, indicating the need for comprehensive analyses of system responses using reliable models.

The complex problem of predicting the OWT performance in the offshore environment thus requires analysis in both oceanography, meteorology and climatology (understanding the patterns and probability of weather hazards), of aerodynamics, hydrodynamics, and geotechnical aspects, of structural, material, control, and electrical engineering (to model and quantify the system response and fragility), and of extreme value analysis to capture correctly the conclusions resulting from analysing data in the tails of the probability density functions. Although many works cover several of these areas, there are no publications covering all areas in all detail. The extensive work by Hallowell et al. [60] included several of the above topics, and investigated the probability of life-time failure at nine wind farm sites along the US Atlantic coast. Using simulated wind and wave data from 100’000 hurricanes and computing the structural response (yielding and buckling) using the software FAST, they concluded that the probability for failure is $9.6 \cdot 10^{-6}$ when the yaw control is working properly, and $2.9 \cdot 10^{-4}$ without yaw control. However, despite being one of the most comprehensive studies in the area, simplifications in each area were required: only one structural failure mode is included, whereas in reality failure could also be expected in blades, turbines, seabed mooring, sea cables, substations and other electrical subsystems. Also, the study by Hallowell et al. [60] was restricted to hurricanes and neglect potential hazards such as winter storms, and considers only a 5 MW monopile OWT. Furthermore, the aerodynamic and hydrodynamic evaluation was carried out by simplified methods, and neglect non-linear effects, which would require computationally costly computational fluid dynamics (CFD) software.

The vulnerability assessment of the offshore structures is further complicated by the complex interdependencies between the different components and subsystems, and by the inability of state-of-the-art methods to capture all subsystems at high fidelity in integrated models. Kang et al. [143] presented a qualitative and quantitative fault-tree analysis for a floating OWT (FOWT). Failure rates for subsystems (support structures, pitch and hydraulic system, generator, gearbox) were collected from databases and published literature. The study concluded that extreme sea conditions, strong winds and waves, are the main cause of structural malfunction. Leakage and over pressure was another large cause of failure in the pitch and hydraulic systems, whereas corrosion and wear was the main cause of gearbox failures. For the entire FOWT, the results showed that the system would fail on average 7.31 times per year, about four times higher than onshore analogues. Using aero-elastic simulations of monopiles exposed to extreme weather conditions, Wilkie and Galasso [144] presented fragility functions displaying the probability for structural failure of different components (tower, monopile, blades, and transition piece) due to the wind and wave loads. Zuo et al. [133] investigated tower and blades fragilities of a 5 MW NREL OWT under different operational conditions using a finite element model and including uncertainties in material and damping. Kapoor et al. [145] modelled the hurricane wind loading using a computationally extensive large eddy simulation, and showed that including wind direction change and veer in the wind field can lead to substantially increased loads. Recently, the methods used to study the vulnerability of offshore wind turbines has been extended to surrogate models and digital twins [146–148], artificial neural networks and machine learning approaches [149–153].

Control systems couple subsystems and affect the dynamics of the OWTs. This can be used both to enhance power output but also to reduce detrimental loads and the vulnerability to hazards. Pustina et al. [154] introduced a fully coupled aero/hydro/servo-mechanical model for the NREL 5 MW OWT and demonstrated its effectiveness in alleviating power fluctuations and vibratory loads. Different blade-pitch and mass–spring control methods for FOWTs were examined and classified by Shah et al. [155], and model prediction was seen to significantly enhance the control systems’ ability to handle load mitigation. A promising approach to enable real-time predictions is by machine learning in combination by condition monitoring. However, as pointed out by Hallowell et al. [60], control systems have often been the cause of failures in reported events of failed OWTs; introducing new complexities come at a risk that need to be considered.

From the above review, we can conclude that there are still significant knowledge gaps in assessing the vulnerability of OWT to offshore environmental loads. These originate from both uncertainties in characterizing the extreme environmental conditions (including determining what can be considered extreme or not, and coupling multiple environmental hazards), in predicting the short- as well as long-time responses of all coupled subsystems to a high accuracy, and in deriving the resulting robustness of the system, considering also material uncertainties and degradation over time. However, only few historical incidents of damages during hurricane-type events have been reported. In China, the Typhoon Dujuan in 2003, the Typhoon Jangmi in 2008, and the Typhoon Yagi in 2024 resulted in the damage and collapse of several wind turbines [156,157]. In Japan, The Typhoon Maemi in 2003 and Typhoon Saomai in 2006 caused the collapse of three and five wind turbines, respectively [157–159]. The reason that only relatively few failures have been reported could be the short history of installations, and the fact that most wind turbines have been installed in shallow waters using fixed monopile foundations. Uncertainties will increase with installations in deeper water and with emerging technologies.

5.2.2. Restoration phase

The recovery after a disruption in an energy system is a complex process, whose outcome, costs, and rapidness depends on a range of factors [14]. The nature and magnitude of the disruption and the system, the availability of spare parts, transportation and personnel, the weather conditions and accessibility allowing for repair or adaptation operations all influence the recovery process. For offshore wind, maintenance or recovery processes make up a critical element in the levelized cost of energy, and have been studied using a range of methods and approaches [160]. With a focus on human and organizational factors, Mentes and Turan [161] implemented resilience engineering principles to maintenance strategies. Using a Monte-Carlo approach, Dalgic et al. [162] evaluated O&M strategies for an offshore wind farm of different transport systems (helicopter, crew transfer vessels, offshore access vessels, and jack-up vessels) under different environmental conditions (wind speed, wave height, and wave period). They concluded, among other findings, that the second half of the year can be too late to start preventive maintenance tasks, and highlighted how the O&M fleets can be operated in a cost-effective manner. Irawan et al. [163] developed a mathematical model to minimize maintenance costs for offshore wind farms, and were able to reduce costs by 12% on average. Costs for vessels, technicians, and penalty costs for delayed maintenance were included, and the results were validated against the work of Dai et al. [164]. Skobiej et al. [165] analysed the relation between the system response of offshore wind farms to severe weather conditions and the redundancy of operating vessels, and found, not surprisingly, that the redundancy had a considerable impact during the recovery phase. In general, offshore operations are limited by the available weather windows, for instance defined by significant wave heights below 1.5 m and mean wind speed below 10 m/s [160]. Xie and Johanning [166] proposed a hierarchical met-ocean selection model, which identifies the most representative data from each month, and were able to reduce the computational cost associated with stochastical simulations of O&M of offshore RES by 98%. Recent works on reliability and O&M strategies for offshore wind farms have also incorporated machine learning and digital twin methods [146,167–170].

5.2.3. Resilience of offshore wind technologies

Whereas the above subsections detailed work on resilience components such as vulnerability and recovery processes, several authors have also addressed a wider scope of the resilience concept for offshore wind systems. Feng et al. [30] presented a design-oriented resilience assessment method, and applied it to an offshore wind farm consisting of ten 3.5 MW OWTs. Using time-dependent functions and sorting the units into different layers ("meta-structures"), different designs were compared for their expected resilience. To bridge the gap between classical risk assessment and resilience management of offshore wind systems, Köpke et al. [171] proposed an approach where the risk assessment, usually based on expert knowledge and qualitative methods, is evaluated using quantitative measures. Liu et al. [172] studied resilience of offshore wind farms from a decision-making and economical reserves perspective, as shown in Fig. 6. Failures of the OWT were derived in two ways; structural failure of the tower and blades as a result of extreme wind- and wave loads were modelled using the FAST software, and failures for mechanical and electrical components were assessed using constant failure rates. The consequences of the OWT failures were assigned economical values as cost of repair and loss of income. The resilience was finally quantified as the economical capacity of the project. Fig. 6 shows a case when the resilience fails, due to a large disturbance using up the economic capacity. Not surprisingly, the study concluded that preparedness, including continuously accumulating an economic buffer from the benefits, is a key factor affecting the resilience of the system.

5.3. Grid resilience as function of wind power dependency

Vulnerability from the perspective of delivering the required power to the grid includes also capacity loss due to wind speed being either below or above the threshold where the OWT produce electricity. The cut-out wind speed is usually around 25 m/s, which is exceeded in hurricane conditions.

The way a system responds to a disturbance can have a significant impact on its overall functionality. As wind turbines are designed to ramp down during extreme wind speeds to reduce the risk of failures, curtailment strategies will affect the resilience of the wind turbines and the dependent electric grid during storm events. Wang et al. [173] proposed an ordered curtailment strategy, to not only guarantee robustness, but also reduce the operating costs of the grid. The method was applied for an IEEE-RTS 24 node grid, with hydropower, thermal, and nuclear power as residual loads. Compared to a simple strategy in which wind power plants stop operating when they reach the cut-off speed or a fixed time before that, the improved strategy resulted in lower operational costs and no load losses.

Mattu et al. [174] studied the risk posed by tropical cyclones on four potential wind farms in Mexico; two in the Pacific Ocean and two in the Atlantic Ocean. They found that Category 4 and 5 hurricanes have potential to cause periods of low power generation due to wind speed cut-out at all four sites, but that the probability of cut-out conditions occurring simultaneously at the four sites was low.

The mere presence of intermittent renewables in the grid may give rise to vulnerabilities that extreme weather hazards may exploit. Smith et al. [175] showed that an increased installation of distributed renewable generation and household storage can lead to a lack of robustness, and that household batteries available on the market would not mitigate these vulnerabilities. Using Sweden as a case study and 29 years of weather data, Höltinger et al. [176] studied the impact of climatic extreme events on the feasibility of fully renewable power systems. They found that an increased share of intermittent renewables would put the system under large stress during severe weather events, and that the thermal and hydropower balancing capabilities were exceeded during those events.

The resilience of the electric grid under hurricane conditions was addressed by Watson and Etemadi [177]. They studied how repair costs and capacity loss would change under increased solar and wind power generation, from present day of 20% to 50% or 80%. Using fragility curves for transmission lines, substations, and electricity generation facilities (coal, gas, nuclear, solar PV, and wind power), they concluded that the capacity loss increased significantly with increased penetration of intermittent renewables. In a similar approach, Satkauskas et al. [178] studied the impact of Hurricane Dolly in a Texas electric grid using fragility curves for the wind turbines and transmission towers. All their 1'000 Monte-Carlo simulations resulted in a disconnected grid network, and the loss of load following the event was computed. Forsberg et al. [179] studied the resilience of the IEEE39-bus New England grid to storm conditions in different scenarios for increasing penetration of offshore wind. They concluded that a penetration level of 30% or less resulted in a power system resilient to hurricane events, whereas a penetration of 50% offshore wind resulted in a disconnected load ranging from 1/3 of the total load demand, to a total power system blackout. The more interconnected UK grid, on the other hand, was seen to be robust under the same weather hazards and wind penetration [180]. This highlights that conclusions made for one system cannot be readily translated to other systems.

Increased penetration of wind energy in the grid does not necessarily only affect the resilience of the grid negatively; some research indicate that renewable energy technologies can be used to improve recovery of the electric grid following disruptions [181]. Several authors have pointed out how functionalities in the new energy facilities can be used to enhance the grid resilience. In a case study of an IEEE 18-bus grid, Su et al. [181] showed that a penetration of 13% wind

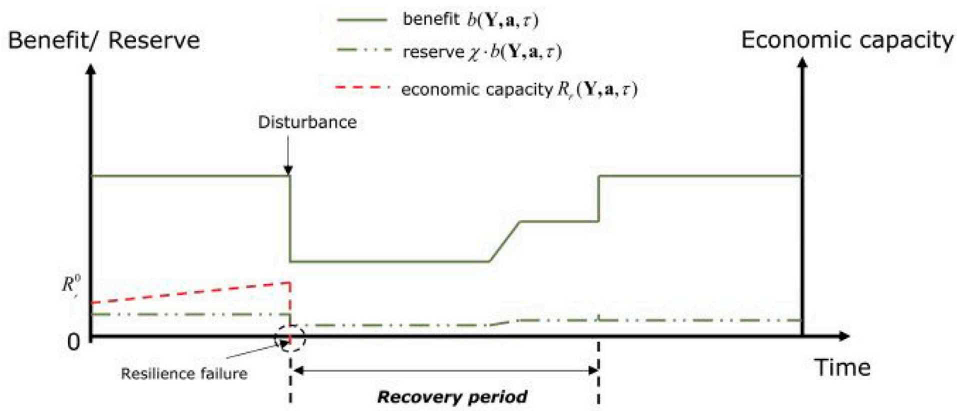

Fig. 6. Resilience of a wind farm, in terms of the economic capacity of the system [172]. The figure shows a case when the resilience fails, *i.e.* when the economic capacity reduces to zero, due to a large disturbance requiring all the economic reserves.

power (corresponding to 3 farms of total 600 MW) could be used to enhance system restoration following a large blackout. The wind farm technologies were considered as non-black-start units, which enabled them to supply electricity faster than the traditional power generation units.

6. Resilience of marine energy systems to extreme weather

As reviewed in Sections 4 and 5, the resilience concept has been applied to power systems and offshore wind energy systems in a multitude of approaches and contexts. For other offshore renewable systems, including wave and tidal energy, resilience has not been studied to the same extent.

6.1. Marine energy technologies and installations

Marine energy has potential to contribute to a large part of the world's energy needs. Kilcher et al. [182], reported that the technical resource, *i.e.* the proportion of the theoretical resource that can be captured using existing technology options, only in the USA is 2300 TWh/yr, equivalent to 57% of the country's current electricity production. Marine energy includes wave energy, tidal energy, ocean and river currents, and ocean thermal energy. Here, the focus is on wave energy and tidal energy, since they are closest to large-scale commercialization. Whereas wave energy technology aims at converting the energy in ocean surface waves (usually into electricity, but direct use to desalinate water or power navigation systems also exist), tidal power converts the energy in tidal ranges or currents. Neither wave nor tidal energy has reached a maturity comparable to offshore wind energy; some promising demonstration plants exist, but the resources are largely untapped. The status of these technologies and installations will here be reviewed.

6.1.1. Wave energy

Even if wind energy technologies differ somewhat, in particular between the fixed and floating concepts, the diversity in wave energy technologies is much greater. Attempts to classify existing wave energy concepts have been provided by a large number of authors; comprehensive reviews can be found in the recent publications [183, 184].

In their pioneering work, Budal and Falnes [185] classified wave energy concepts according to their orientation with the incident waves: perpendicular to wave direction (terminators), along with wave direction (attenuators), and independent of wave direction (point-absorbers). Falcão [186] classified the concepts according to dynamical working principle as oscillating water columns, overtopping devices, and oscillating bodies. A database of capture width ratios for wave energy converters (WECs) was provided by Babarit [187], who also used the dynamical principle as basis for the classification. Each of the WEC categories can further be classified into submerged or floating structures, as well as according to their location of installation: onshore, nearshore, or offshore. López et al. [188] did an attempt to classify WECs according to three dimensions of working principle, location, and orientation. Mofor et al. [189] added yet another dimension of the power take-off (hydraulic, direct-drive, hydro, pneumatic). Examples of the main classes of WECs are shown in Fig. 7. The classifications are somewhat ambiguous; some WECs fit in several classes, whereas other fit in none of the above. In each of the mentioned classes of WECs, there is also a multitude of different WEC concepts at varying stages of technology readiness level, ranging from conceptual ideas to full-scale deployed devices. This lack of convergence towards one or a few technologies could be one of the reasons explaining why wave energy has not yet reached a maturity level comparable with offshore wind (together with the fact that fixed offshore wind builds on a combination of already established onshore wind and traditional offshore structures).

Due to the massive amounts of WEC concepts, it is not feasible to review all. Here, some major WEC technologies that have been tested at a large scale in an offshore environment are reviewed. *Oscillating water columns (OWC)* consist of a hallow chamber partially submerged below the ocean surface, with opening below the minimum wave level. The column of air that is trapped above the water surface is forced through an air turbine when the water level is rising or falling due to the incident waves. A direction-independent turbine such as the Wells turbine is used, so that energy can be extracted during both inhale and exhale phase. Examples of OWC installations are the Toftestallen, PICO, LIMPET, and Mutriku wave power plants. Examples of floating OWCs include the OE Buoy, Oceanlinx, Mighty Whale, and the Sparbuoy. *Overtopping devices* build on an operating principle similar to hydropower. Incident waves are overtopping into a reservoir, thus converting the wave energy into potential energy. Similar to a hydropower plant, the collected water passes a turbine at the reservoir outflow when leaving the basin. The Wave Dragon, OBREC, and TAPCHAN are three examples of overtopping WECs that have undergone sea testing. *Attenuators* are oriented parallel to the wave direction, and have a long structure compared to the wave length. The WECs usually comprise several cylindrical sections linked by hinged joints, and energy is extracted from relative motion between sections. The most famous attenuator is Pelamis, but other examples include Blue X and the McCabe wave pump. *Oscillating wave surge converters (OWSC)* are oriented perpendicular to the wave direction. They consist of one or several paddles, fixed to the seabed or a floating reference, that are forced into pitch motion by the surging motion of the waves. The paddle motion can then be converted, *e.g.* using hydraulic pistons. Examples include the Oyster,

Fig. 7. Examples of wave energy converters. (a) OPT PowerBuoy, a point-absorber; (b) OBREC, an overtopping device [190]; (c) Pelamis, an attenuator [191]; (d) WaveRoller, an oscillating wave surge converter; (e) Mutriku wave power plant, oscillating water columns [192].
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Wave Roller, Exowave, and Pendulor WECs. Probably the largest class of WECs are the *point-absorbers (PAs)*. They differ significantly in their operational principles, but share the common feature that they are independent of the wave direction and that their horizontal dimensions are small in relation to the wave length. Most PAs are oscillating bodies that are comprised of a floating or submerged buoy connected to another fixed or floating structure. The buoy is forced into oscillation by the waves, primarily in heave, and the relative motion to the second body is used to extract energy. Examples that have undergone sea testing include CorPower, WaveStar, Eco Wave Power, Zhoushan, Changshan, CETO, OPT PowerBuoy, Waves4Power, Archimedes Wave Swing, Wavebob, Ocean Harvesting, and the Uppsala University WEC.

Examples of these five WEC categories are shown in Fig. 7. Some promising WEC concepts do not fit in any of the listed categories, for instance WEPTOS (arrays of multiple pitching buoys) or Penguin (rotating mass pendulum). Out of the listed WEC technologies, many have been discontinued. Mutriku, installed at a breakwater structure in Spain, is one of the few examples demonstrating continuous operation since its installation in 2011. Several others, such as CorPower, Changshan, Blue X, and Penguin, have been tested in the offshore environment during limited periods of time, and have reported recent design improvements and plans for further offshore experimental campaigns.

6.1.2. *Tidal energy*

Tidal power plants convert the energy from tides into electricity. Compared to wave energy, tidal energy has reached a higher technological maturity; tidal stream energy had accumulated around 1.4 million operating hours in 2021 [193]. Following time cycles with origins in the Earth–Moon–Sun systems, tidal energy is more predictable than wind and wave energy. The dominant tidal constituent is the principal lunar semi-diurnal cycle of 12.42 h. Together with the principal solar semi-diurnal cycle of 12 h, it leads to the spring-neap cycle, with enhanced tidal range during full moon or new moon [194]. The global potential of tidal energy is larger than for wind and wave [195]; the tidal dissipation in shelf sea environments is around 1.7 TW [194]. However, there are only few areas in the world suitable for tidal energy extraction. These are characterized by large tidal ranges, *i.e.* the difference in height between high and low tide. Neap and spring tides with a tidal range of 4–12 m have a power production potential of 1–10 MW/km [196]. The largest tidal range is found in the funnel-shaped Bay of Fundy, Canada, and measures up to 16 m.

There are two main approaches to capture the energy in tides. Tidal range power plants convert the potential energy in tides, and tidal stream power plants capture the kinetic energy. The tidal range technologies can further be classified into tidal barrages and lagoons. The different categories are discussed below, and examples are shown in Fig. 8.

Tidal barrages collect incident tides in large dams and thereby store their potential energy. The dams are constructed across the full width of a tidal estuary. The potential energy is converted into mechanical energy as the water is released through large turbines, similar to hydropower. The La Rance tidal barrage power station was constructed in France already in 1966. It comprises a 720 m long barrage, spans an area of 22 km^2 and has an installed capacity of impressive 240 MW. It has only been surpassed in rated power by the 254 MW Lake Sihwa barrage that was constructed in 1994 and finalized in 2011 in South Korea. Other operating tidal barrages include the Jingxia Tidal Power Station in China (3.2 MW), the Uldolmok Tidal Power Station in South Korea (1.5 MW), and the Eastern Scheldt Barrier Tidal Power Plant in the Netherlands (1.25 MW) [195]. The Annapolis Royal Generating Station tidal power plant was installed in the Bay of Fundy in Canada, with a rated peak power of 20 MW. It operated for 34 years since 1984, but was shut down in 2019 due to substantial fish mortality caused by the turbine.

Whereas tidal barrages span the entire tidal estuary, a *tidal lagoon* encloses an area of coastline with a high tidal range behind a retaining walls. By not blocking the entire flow of water into and out of a tidal estuary, tidal lagoons are envisioned to have less environmental impact than tidal barrages. The tidal lagoon Swansea Bay in the Bristol Channel, UK, is a tidal lagoon power plant proposed to be located at a site with spring tidal range of 10.5 m and with a nameplate capacity of 320 MW [194]. Development consent has been granted by the UK and Welsh governments, but since the UK government withdrew its support in 2018, the future of the installation is unclear.

Unlike tidal barrages or lagoons, *tidal stream* technologies utilize the kinetic energy of tidal currents. Due to the much higher energy density in water as compared to air, even slow water speeds can be used to extract much energy. Most tidal stream concepts are based on a technology similar to wind power, with vertical or horizontal axis turbines. Other approaches also exist, such as underwater kites and oscillating hydrofoils [197]. The Race Rocks Tidal Current Generator was a 65 kW demonstration tidal stream turbine installed 2006–2011 in Victoria, Canada [198]. The SeaGen tidal stream generator had a capacity of 1.2 MW and was installed on the east coast of Northern Ireland in 2008–2019. The MeyGen tidal energy project consists of four 1.5 MW turbines with 16 m rotor diameter. They were installed in 2017 on the seabed close to the castle of Mey in Scotland, and plans exist on expanding the site to a total of 400 MW.

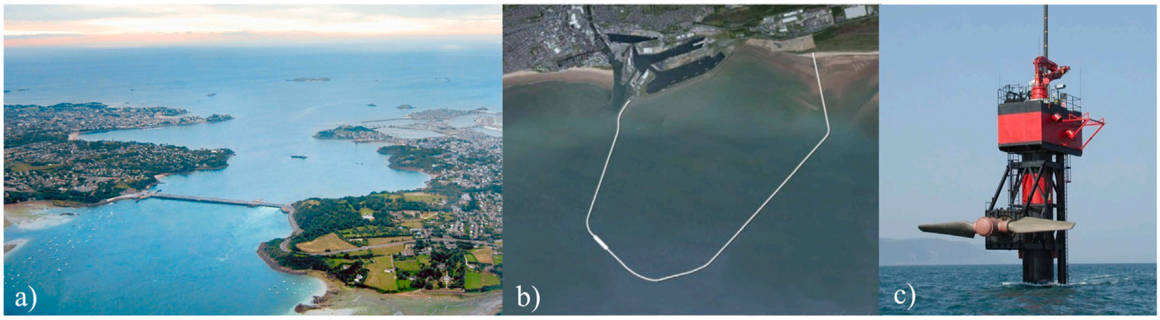

Fig. 8. Examples of tidal energy technologies. (a) The La Rance tidal barrage, France; (b) The planned Swansea Bay tidal lagoon, UK; (c) The Seaflow tidal stream turbine, a 300 kW predecessor of the SeaGen turbine, UK.

6.2. Resilience of wave energy systems to metocean conditions

Clark and DuPont [199] concluded that, apart from fixed offshore wind, little work has been published on reliability-based design of offshore renewable energy systems. For wave and tidal energy, this could be understood from the fact that these systems are still in their demonstration phase, and also that there is a considerable divergence in the technologies, as reviewed in Section 6.1. Even if methodologies can be adopted from more established energy technologies to assess the resilience of emerging wave energy technologies, there are several fundamental differences that make translations of conclusions difficult. One major difference is that wave energy converters often are much smaller than offshore wind turbines, and that they are designed to operate in resonance with the incident waves.

6.2.1. Absorption phase

As discussed in Section 5.2.1, vulnerability to the external environment has been identified as one of the main challenges for offshore wind systems [200–202], and it is reasonable to expect that less mature and more dynamic wave energy systems will be even more exposed to these vulnerabilities.

There is an extensive literature on the vulnerability of wave energy systems to extreme environmental conditions. Most analyses have been numerical simulations of WECs (or subsystems thereof) in severe or extreme wave conditions [203,204]. As pointed out by Jonathan and Ewans [205], it is not a trivial task to determine which wave conditions that should be considered "extreme". This was the case also for OWTs as discussed in Section 5.2.1; for WECs this issue is even more challenging due to most the small scale and dynamical design of wave energy systems. The impact will depend on many factors, including the device's working principle, dynamics and dimensions, and control strategies. Typically, the impact of a range of wave parameters on or within an environmental contour with return period of 50–100 years is used, as exemplified in Fig. 9. The dynamics in these wave conditions typically involve highly non-linear effects such as overtopping on the floating structure or snatch loads in mooring lines. CFD simulations of WECs in extreme waves have been conducted using both mesh-based [206–211] and particle-based software [212–214]. High-fidelity CFD models have also been compared to models of lower fidelity in a range of works [215–218]. To invoke trust in the numerical simulations, blind-comparative studies have been carried out, where participants carry out simulations for a given system and submit the results without prior access to the physical data [219–221].

A significant knowledge gap relates to the scarcity of data needed for validation and prediction. Experimental studies of WEC dynamics and survivability in extreme wave conditions come with many challenges; in particular from the physical constraints of the wave tank and experimental set-up. Nonetheless, there exists a body of literature on wave energy systems in severe metocean conditions carried out in wave tanks [224–228] The experimental data has also been used for the important task to validate numerical models [229–235]. Data from

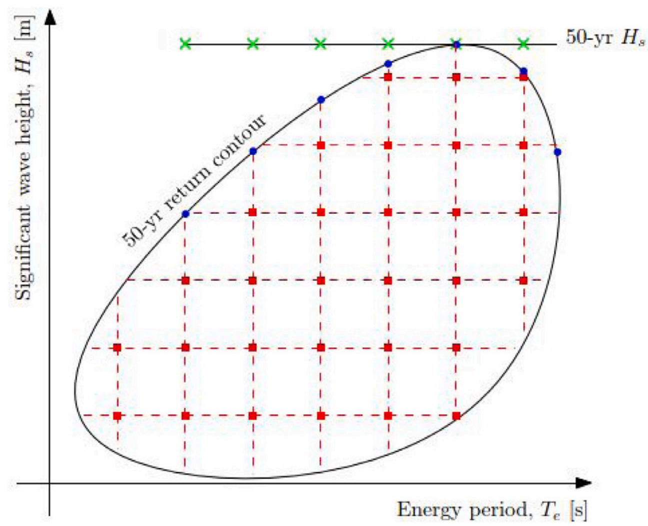

Fig. 9. Environmental 50-year contour, defining extreme sea states in terms of significant wave height and energy period [222].

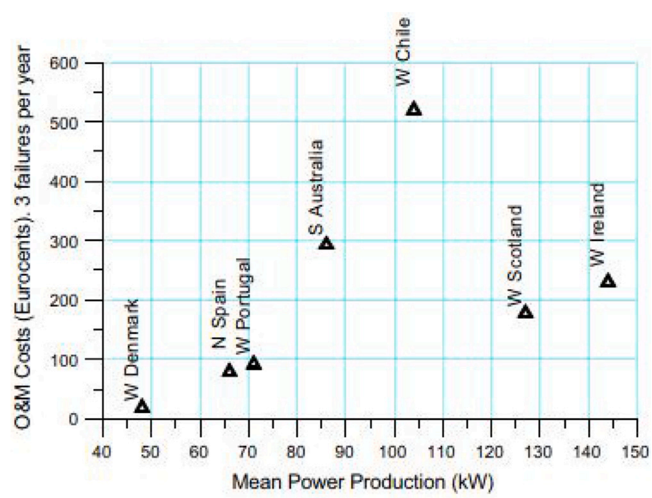

Fig. 10. Economical assessment of O&M costs for a wave farm with a failure rate of 3/year, at seven offshore sites, compared to the average power production [223].

offshore operations exist [236,237] but is very rare due to the very short accumulated installation time of WECs.

Based on results of numerical and experimental studies of WEC survivability and established knowledge from traditional offshore engineering, there have been various attempts in developing general guidelines and practices for reliable wave energy design [222,238–247], to derive failure rates for wave energy systems in various conditions [248–257], and to optimize wave energy system based on reliability objectives [258], but the large diversity in technologies complicates drawing general conclusions.

6.2.2. Restoration phase

Similar to offshore wind systems, maintenance and repair operations at offshore sites can only be conducted during calm weather conditions. Due to these constraints, several authors have identified that downtime related to failures constitute major costs for wave energy systems [199,259,260].

Accessible weather windows open for maintenance and repair operations of offshore renewable installations have been analysed for different locations and vessel options in [43,202,223,255,261–266]. In several of these works, the accessibility analysis was connected to probabilities of operation failures of the wave energy systems. There have also been approaches of connecting the offshore operations to the financial returns [223,257,260,267]. For instance, Guanche et al. [223] mapped O&M costs for wave farms at different offshore sites and for different annual failure rates, as shown in Fig. 10. In the European Commission report [268], procedures for assessing accessibility of marine energy sites were outlined, in which the time-series approach was recommended over the simpler stochastic method.

Mérigaud and Ringwood [269] discussed the accessibility challenges associated with offshore marine energy, and analysed how condition-based maintenance and prognostics can help to optimize maintenance activities and forewarn of impending maintenance requirements. A reliability-based computational tool was presented by Rinaldi et al. [263]. By varying strategies for vessels, maintenance regimes, failure rates and component redundancy, the tool aimed to reduce costs and increase productivity of a wave farm. A review of O&M planning of offshore renewable energy farms was provided by Rinaldi et al. [270], who foresaw that advances in robotics, artificial intelligence and data processing lead the way to more automated offshore operations.

6.2.3. Resilience of wave energy systems

As reviewed in Sections 6.2.1–6.2.2, numerous works have addressed elements of resilience for wave energy systems, in particular the vulnerability to environmental conditions, and repair operations as functions of weather windows. However, even if several of the works reviewed in Section 6.2.2 have included both failures and repair operations in their analyses, very few have explicitly applied the concept of resilience to wave energy systems [257,271], and assessed both the absorption and restoration phases coherently. Assuming that WECs are designed to survive rough seas, Korde [271] used resilience as a means to power early recovery operations and to support power-grid blackstart. Göteman et al. [257] derived a metocean-dependent failure rate of WECs, and used it to analyse the resilience of large wave farms during weather conditions measured over one year. Different repair strategies were evaluated based on their ability of restoring the system following disruptions, and their costs.

Resilience from the perspective of maintaining electricity supply during grid outages has been studied with a focus on wave energy by Newman et al. [272]. By adding wave energy to the Hawaii grid, their work demonstrated how wave energy resources, with energy source profiles that are not coincident with PV and wind profiles, can offer microgrids a higher level of reliability and resilience. Similarly, with the aim to provide an enhanced grid resilience, Men et al. [273] implemented multiple networked microgrids surrounding marine energy resources as well as energy storage units.

In summary, we can conclude that the knowledge gaps on resilience of wave energy systems are significant. Whereas some methods to assess the restoration phase can be adopted from offshore wind, the absorption phase differs fundamentally due to the scale, dynamics, and diversity in wave energy technologies. Above all, data from fullscale devices and offshore operation are almost non-existing in the literature, making validation as well as prediction difficult.

6.3. Resilience of tidal energy systems to metocean conditions

Although tidal energy has reached a higher commercial scale than wave energy, there are only a handful of tidal energy installations in the world. Similar as to wave energy, there is very little available field data relevant for reliability or resilience studies [274–276], including economical parameters [277].

6.3.1. Absorption phase

Reliability and vulnerability assessments of tidal energy systems as function of environmental loads have been assessed in several works [278]. Due to the limited accumulated operational time of tidal turbines, standard reliability predictions based on a statistical assessment of historical failure data are rare, and most works are based on numerical simulations or small-scale experiments. Walker and Thies [193] reviewed tidal energy technologies from the perspective of reliability and failures, and concluded that the most common failure cause reported in literature was blade failure, followed by generator and monitoring failures. They argued that most blade failures were attributed to an underestimation of loads during design, which highlights that numerical and experimental work to quantifying environmental loads on turbines is of highest relevance in obtaining reliable systems.

To quantify the environmental loads and their impact on turbine components, many authors have carried out CFD simulations [279–283] as well as physical experiments [284–291] of turbines in different flow scenarios. A recent review on structural testing of tidal turbine blades was provided by Munaweera Thanthirige et al. [292]. Operational fatigue loads induced on tidal turbine blades were studied using the CFD software ANSYS CFX by Finnegan et al. [282], who concluded that the loads could vary by up to 43% of the maximum total thrust force. Ahmed et al. [279] used both Reynolds-averaged Navier–Stokes (RANS) and large eddy simulations (LES) to study the fluctuating loads on a 1 MW tidal turbine, and compared with experimental data obtained at the offshore EMEC site, see Fig. 11. They found that both RANS and LES were able to predict similar phase-averaged loads and blade pressures in low-turbulence scenarios, and thus that a RANS approach would be sufficient to determine mean loads near operating conditions. Ouro et al. [293] used validated LES simulations to show that turbulence increased the range of the structural loads on the blades. An experimental methodology to generate turbulent flows of different characteristics within a flume was presented by Blackmore et al. [285], and used to measure rotor thrust, torque, and blade root bending moments. Milne et al. [284] investigated the streamwise turbulence intensities on the blades in small-scale experiments, and a morphing blade concept designed to reduce fluctuations in the root-bending moment, thrust and torque was experimentally demonstrated by Gambuzza et al. [291]. Martinez et al. [288] investigated experimentally the impact of combined oblique waves and currents on a horizontal axis turbine, and found that the rotor torque and thrust standard deviations are higher in the presence of waves and almost twice as high when the wave crest is parallel to the rotor plan. Translating small-scale experimental results to full-scale conclusions is, however, not trivial [285].

The commonly used assumption of constant failure rates was challenged by Ewing et al. [275], who concluded that pitch systems, generators and frequency converters cannot be considered to have constant failure rates. Based on historical reliability data from comparable wind turbines and other relevant marine databases, Delorm et al. [274] derived reliability models for four 1–2 MW horizontal-axis tidal stream devices. The harsh conclusion of the work stated that the reliability could be expected to be lower than wind turbines, and that few devices could be expected to survive more than a year in the water. An contradicting conclusion was presented by Ewing et al. [276], who derived a failure rate model for a tidal turbine pitch system using empirical physics of failure equations. The resulting failure rate was found to be 50% lower than a comparable wind turbine, however, high reliability

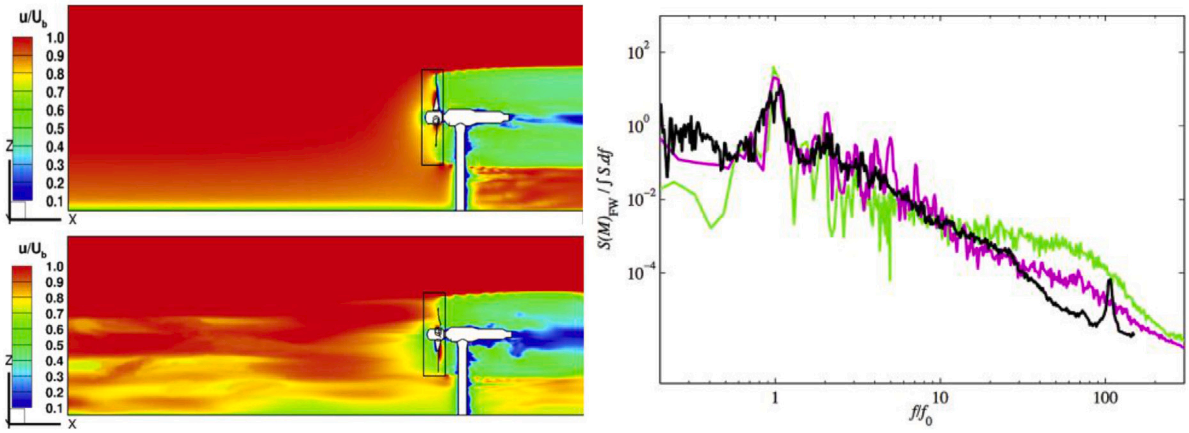

Fig. 11. Examples of LES simulations compared with experimental data. *Left:* Wind velocity field modelled using LES; in the upper figure with no inlet turbulence, in the lower with synthetic turbulence with increased stresses and reduced length scales. *Right:* The spectrum of flapwise bending moment normalized by total variance; experimental data (black), LES with no inflow turbulence (green), and LES with turbulent inflow (purple).
Source: Figure adapted from [279].

requirements had been assumed for the tidal power plant. Fatigue loading on a DEEP-gen 1 MW horizontal axis turbine installed at the EMEC site was modelled by Mullings and Stallard [294]. Reliability and failures of tidal systems based on dependencies of subsystems has been assessed in several works, both on a single turbine level [295], and for cascading failures in a farm [296]. Target reliability levels for tidal stream devices were explored by Khalid et al. [297], and the influences of metocean parameters on subassembly failure rates was assessed. Probabilistic models for reliability assessments of tidal power plants have been developed and applied in a range of works, and applied to various components and environmental conditions [256,298–300]. Advanced statistical tools such as Bayesian network techniques can reduce the unavailability associated with limited real data [256] and aid developers with optimal design strategies [301].

6.3.2. Restoration phase

Many of the works discussed in Section 6.2.2 on the restoration phase of wave energy systems are relevant for tidal energy as well. In particular, the accessibility analyses for various vessels and installation sites given in [43,200,202,261,266,268], were not restricted to wave energy, but are relevant for offshore renewable energy installations in general. The same holds for evaluation of reliability metrics [199,243,248] and maintenance strategies [166,269,270]. Rinaldi et al. [302] applied a reliability based simulation tool for management of offshore renewable energy systems to a conceptual tidal energy farm installed off the north coast of Scotland.

A cost model including O&M for a tidal energy farm was presented by López et al. [277]. Failure rates were obtained from a reliability data base, and the costs for repair of each failure was estimated, including spare parts and vessel costs. In their report on best practices for O&M of marine energy systems, Weller et al. [303] provided guidelines on how to reduce O&M costs for wave and tidal energy arrays. These included strategies to reduce risks of failure (*e.g.* component testing to improve reliability predictions), reduce costs of offshore operations (*e.g.* improved remotely operated vehicles to reduce reliance on expensive dive teams) and intelligent maintenance scheduling (*e.g.* predictive maintenance scheduling based on reliability data).

6.3.3. Resilience of tidal energy systems

There is an abundance of published works for tidal energy systems on the absorption phase, *i.e.* the vulnerability to different environmental loads. Most studies have focused on reliability in operational conditions and less on high-impact, low-probability event. Similarly as for wave energy, comprehensive assessments of resilience of tidal energy systems to severe metocean conditions have not yet been conducted. However, as the subsea environment is less exposed to the atmosphere than at or above the sea surface, tidal energy systems are expected to be less exposed to extreme weather and metocean hazards than wave or offshore wind. Some of the offshore strategies discussed in Section 6.3.2 have incorporated elements along the full resilience curve, even if the concept of resilience was not stated explicitly.

The approaches of improving the resilience of the electric grid by diversifying the energy portfolio is relevant for tidal as well as for wave and wind energy. Explicitly, this was discussed by Men et al. [273], who analysed the coastal community resiliency enhancement obtained by integrating marine energy sources in the grid. Likewise, in the recent work by Coles et al. [304], it was found that the inclusion of tidal stream energy alongside solar and wind has the potential to enhance energy system security and resilience.

7. Knowledge gaps and future directions

Based on the review presented in the earlier sections, it can be concluded that the state-of-the-art of offshore energy system resilience is rapidly evolving. However, several important knowledge gaps remain. The recent work by Wang et al. [21] points out that investigations on energy resilience, such as evaluation indicators and resilience enhancements, are still in their infancy. This is particularly true where emerging offshore RES are involved.

7.1. Threat assessment

To assess the resilience of energy systems with offshore RES to extreme metocean conditions, accurate models of the environmental hazards is required. During storm conditions, wind and wave loadings are typically non-linear and turbulent, and the dynamics needs to be resolved by high-fidelity CFD software. While this has been partly done for aerodynamics and partly for hydrodynamics, a complete assessment including high-fidelity simulations of all involved environmental loads connected to the structural and dynamical modelling of the RES is still missing. With advances in high-performance computing, this is an issue that can be assessed in the near future.

There are still significant uncertainties concerning the impact of global warming on large-scale dynamics, which imposes uncertainties on local and regional changes in extreme events, including changes in extreme wind, wave, and icing conditions. With possible expansion towards Arctic areas additional extreme conditions might increase in importance, this includes polar lows [305], cold air outbreaks, and snow canons [306]. The uncertainty in the hazard prediction is connected to the lack of measured weather data to be used as input or as validation of numerical codes and the resulting uncertainty in the extreme value distributions. Typically, one can find several decades of data at a specific location, but the number of data points in the tail of the distribution remains low. Only a scant among of research has been presented on how climate change may affect energy resources, such as tidal resources [194]. Pelling and Green [307] studied the Bay of Fundy tidal energy site, and found that a 1 m rise in mean sea level would lead to an increase of 0.1 m in tidal range amplitude. Pickering et al. [308] assessed the effects on tidal ranges of changing sea levels at a global scale and found both increases and decreases at different sites. Due to significant uncertainties and lack of data, it is difficult to draw general conclusions on the impact of climate change on metocean conditions and wind, wave, and tidal resources, hence constituting a knowledge gap in need of further research.

7.2. Absorption phase

The energy system is undergoing a vast transformation due to the widespread installation of renewable energy technologies, electrification, and digitalization. To assess the resilience of the future energy system – to possibly new unfolding threats – is inevitably associated with many unknowns. At the system level, different energy sources operate at different temporal and spatial scales; the modelling of multiple energy systems is a challenge [309], and the responses of different energy systems to disturbances vary greatly [21]. In addition, demand response in future energy systems is dependent on many unknown factors, making load modelling uncertain. A high penetration of intermittent renewable energy sources will impact the stability and regulatory properties of the grid, affecting its ability to handle disturbances.

In grid scenarios with high penetration of offshore RES, vulnerabilities in terms of low power generation due to metocean parameters like wind speed below or above the threshold for electricity generation must be fully understood. The risks will depend on the farm distribution scenario; thus each site, technology, and installation scenario must be assessed in its own context. In addition, vulnerability will largely depend on the mitigation methods at hand; curtailment, reserve capacities, and control strategies will affect the vulnerability and need to be optimized to reduce the risks. During hazardous events, there may be many disruptions in different parts of the grid—hundreds of components both in the offshore RES and in transmission systems onshore can be damaged. The correlation between multiple failures and cascading events can lead to large blackouts and must be better understood.

Due to the limited accumulated time of offshore RES operating and delivering electricity to the grid, there is almost no data or empirical knowledge of the vulnerability of these energy systems – or the power systems largely depending on them – to extreme metocean hazards. There has been ample work to assess the vulnerability using numerical models or small-scale tests, but these are by definition always subject to simplifications, and contradictory conclusions exist in the literature. Most work has been focused on fixed monopile offshore wind turbines in parked conditions. Due to the abundance of emerging RES technologies that differ fundamentally in their dimensions, dynamics, and operational principles, conclusions drawn for one system cannot necessarily be translated to another. Which conditions that are considered extreme may differ for different technologies based on the device's working principle. Much more work is needed on different offshore RES, especially emerging technologies such as floating wind.

Vulnerability assessments must also become more comprehensive and address more realistic loadings and scenarios. Even if a great deal of work has been done to assess fragility in separate failure modes of various offshore RES technologies (such as bending modes in monopile offshore wind structures), little work has been done on assessing ultimate load failures in several – possibly interacting – components and failure modes, due to external environmental hazards. As discussed in Sections 5.2.1 and 6.2.1, there have been recent advances in assessing the long-term device response and vulnerability of offshore RES to different metocean conditions, but uncertainties related to both threat assessment and their impact on the offshore RES are still significant [139]. Addressing these knowledge gaps is critical for understanding and mitigating the risks of the increasing dependency on offshore RES, in particular for emerging technologies such as FOWTs and WECs. To increase the accuracy of predictions and the effectiveness of risk mitigation strategies, efforts should be made to improve the resolution for environmental loads (*e.g.*, wind turbulence intensity or coupling between wind, waves and currents [138,139]), the device response (*e.g.*, coupling between components, material degradation, and nonlinear effects [139,310,311]), and developed strategies for monitoring and control [154,155]. The rapidly developing field of CFD models and access to high-performing computer clusters also enable studies including more realistic aerodynamic and hydrodynamic models and loads.

7.3. Restoration phase

Most research on energy resilience has focused on the draw-down phase of the resilience curve, including vulnerability, robustness, and redundancy [20]. The rebuild received much less attention, which creates a knowledge gap. Restoration processes pose a particular challenge for offshore RES, and several authors have concluded that offshore maintenance and repair operations are extremely complex, weather dependent, and costly [160,199,260].

As reviewed in Sections 5.2.2, 6.2.2, and 6.3.2, there have been many recent efforts to assess the strategies and costs of maintenance and repair operations for offshore RES. However, due to the scale of the complexities and uncertainties involved and significant differences between offshore RES technologies, all studies are heavily dependent on context, and it is difficult to draw any general conclusions. For power systems, although emergency planning and restoration following large disruptions has been discussed in many works, only a limited number of studies provide a comprehensive and generic approach to emergency operation and resource allocation during extreme disturbances [312]. For offshore RES, such comprehensive studies are even rarer. Systemic models are needed with which different repair and restoration operations can be prioritized.

Chester et al. [313] argue that the conventional administrative infrastructure governance must be replaced by agile leadership structures to navigate the increasingly uncertain and complex conditions of tomorrow's energy systems. In the approach by Arab et al. [312], a proactive recovery strategy was proposed in which, for instance, repair crew can be mobilized prior to the event if damage is expected from modelling scenarios, similar to work relating to response planning of electricity distribution systems during hurricanes [314]. In addition, in the decision process during a blackout scenario, knowledge of the societal impact of the disturbance (*e.g.*, the electricity shortage) is needed; there is thus a knowledge gap in developing more holistic tools embracing both technical aspects and societal values, which is discussed in greater detail below.

7.4. Resilience of offshore RES and socio-technical interdependencies

With an increased understanding on the vulnerability of energy systems with higher penetration of offshore RES to extreme metocean conditions and their ability to recover from disturbances, more complete resilience aspects of these systems can be addressed, along the lines of what has been done for the power systems reviewed in Section 4. As societal functioning is heavily dependent on electricity supply, and all critical infrastructures are interconnected, energy resilience is as much a socio-economic as technical question, and the societal losses

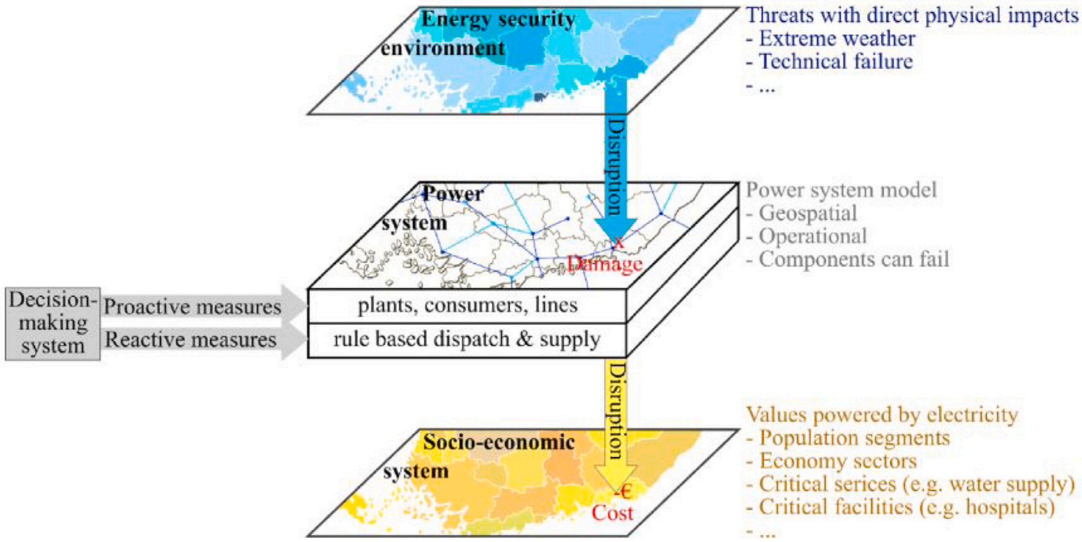

Fig. 12. Framework for linking disruptions in power systems with socio-economic aspects, as illustrated by Jasiūnas et al. [322].

could significantly exceed utility infrastructure losses [315]. Panteli and Mancarella [14] argue that human response must be included as a key dimension when assessing the resilience of power systems. Social stability, national security, economic development, and even human lives are at stake if the electricity supply cannot be guaranteed [316,317], as illustrated in Fig. 12. Various models are often used to model interdependencies in energy system, and involve supply–demand models [318], energy-economy-environment models [319], water-energy-food nexus models [320], and the like. Each focuses on different social, economic, and political aspects [321], but in general incorporating social metrics into the models is far from standard. As Jasiūnas et al. [322] point out, existing research connecting technical and socio-economic aspects in modelled scenarios of energy system disturbances is limited.

Socioeconomic aspects can be studied by both qualitative and quantitative methods. The qualitative studies are often empirical, and include approaches such as surveys or interviews with experts, key personnel, and witnesses, workshops with stakeholder representatives, and field studies. Quantitative approaches include coupling models of the energy systems with models of other critical infrastructures and/or societal metrics. Jasiūnas et al. [322] connected a model of the Finish electric grid with GIS maps of social and economic values, such as population, economic activity and critical services. When modelling the system during a two week storm disturbance, they found that the cost of the power outages could be significantly reduced by controlling their location but also that prioritization of one socio-economic value may increase the costs in another. Similar conclusions have been reached in several studies, which also emphasize that the vulnerability of the population to power outages is not even; the elderly, children, linguistic minorities, and low-income households are often at greater risk [323].

In the context of offshore RES, no studies have as yet incorporated societal aspects into their resilience assessments, even if a few have assigned economic values to resilience metrics. A recent example of a resilience assessment of offshore RES that includes decision-making and economic perspectives was provided by Liu et al. [172], who connected decisions on putting away certain amounts of the economical benefits to the economic resilience of the OWT project.

Related to socio-economic resilience are the interdependencies between infrastructures and societal actors. Many disruptions in energy systems are cascading events, such as the 2003 blackout in Canada and USA and the Venezuelan blackout in 2009 [21]. The increasing interdependencies between the electric grid and other infrastructures and societal functions create complexities for which most existing studies of energy system simply do not account [82]. Interdependencies within or between energy systems and other critical infrastructures have been studied by a range of methods for power systems in general, as reviewed in Section 4, but this has not yet been carried out with a specific focus on energy systems with offshore RES. The authors stress the need for such more comprehensive research studies.

8. Conclusions

This paper provides a review of the research efforts that have been dedicated to assessing and improving the resilience of offshore renewable energy systems (RES) to weather and metocean conditions. Due to the increasing dependence on the electricity delivered by these systems, this is a concern that must be addressed to guarantee the resilience of the society of tomorrow. By identifying knowledge gaps in building resilient renewable energy systems, the paper aligns with the UN SDGs and Climate Change Framework related to ambitions to build affordable and clean energy systems, sustainable societies, and battling climate change.

To set the context, the concept of resilience was presented and then compared to related terms. We discussed the effect of hazards – extreme weather and metocean conditions – on vulnerability and resilience of offshore RES. In power systems research, resilience to extreme weather events has been a well-established topic for at least a decade. This body of work was reviewed, as some of the approaches and methods are applicable to offshore RES, though others are not.

Resilience, from an engineering and natural hazards perspective, is often described in terms of the resilience curve, the temporal dependence of which can be roughly divided into the absorption and restoration phases. The former describes the loss of system functionality following a disturbance and is related to the vulnerability of a given system to a hazard. The restoration phase describes the ability and rapidity of the system to recover after a disturbance. Despite the vast literature that has been presented on assessing these two phases for offshore RES as well as the grid during hazardous events, there are still large unknowns that need to be addressed. Extreme weather impact under climate change, comprehensive vulnerability assessments in realistic conditions, and response planning in the offshore environment are examples of areas in dire need of further attention.

More complete resilience assessments of offshore RES to extreme conditions, incorporating the system capabilities before, during, and after disruptions, are rare. For offshore wind, some recent work has presented a resilience assessment and connected vulnerability to system restoration, and there is also a body of research assessing the resilience of the electrical grid with a large penetration of offshore wind. For wave and tidal energy systems, these issues have not been addressed to the same extent. This knowledge gap can be understood as partly due to low technical maturity of emerging offshore RES and partly to the great diversity in technical approaches, especially for wave energy. Due to the limited accumulated operating hours, there is very little real-world data on vulnerability and other elements of resilience for these systems. In combination with unknowns arising from climate change and transformations in the power system, the uncertainties are extensive and the need for new knowledge immense.

CRediT authorship contribution statement

Malin Göteman: Conceptualization, Methodology, Investigation, Data Curation, Writing – original draft, Writing – review & editing, Project administration. **Mathaios Panteli:** Investigation, Writing – review & editing. **Anna Rutgersson:** Investigation, Writing – review & editing. **Léa Hayez:** Investigation, Writing – review & editing. **Mikko J. Virtanen:** Investigation, Writing – review & editing. **Mehrnaz Anvari:** Investigation, Writing – review & editing. **Jonas Johansson:** Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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