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Hybrid Renewable Energy Systems: Challenges and Research Opportunities

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Abstract

This study aims to develop an innovative load redistribution model to systematically assess the resilience of the European container shipping network (ECSN) against the cascading failures. The new model pioneers the examination of the impact of port selection preferences (i.e., evenness, connectivity, betweenness and scale) on load propagation and the systematic assessment of resilience in terms of both connectivity and vulnerability. The thorough analysis and case studies of 172 European ports indicate that the disruptions in Port of Rotterdam would result in the most vulnerable network. For enhancing the resilience of the ECSN, this study suggests two key strategies: implementing the weight-based redistribution rule and maintaining adequate reserve capacity. This work offers valuable insights for port and logistics stakeholders in managing unforeseen risks and in the planning and development of port infrastructure.

Keywords: Resilience analysis, European container shipping network, Cascading failures

1. Introduction

Access to electricity is now a necessity rather than a luxury. The presence of reliable power is crucial for safeguarding the economic and political stability of a country. Various sectors, including industry, communication, national security, healthcare services, and access to clean water, heavily depend on a consistent power supply (Macmillan, et al., 2022). This dependency becomes even more apparent, as seen, for example, during the challenges posed by the COVID-19 pandemic and the potential disruptions in power that may arise due to natural disasters (Modaberi, et al., 2023). To ensure the security of the power system and reduce the effects of disruptions, it is crucial to evaluate potential risks and explore viable pathways to enhance resilience in the power system. Resilience, though defined differently across various sectors, is principally concerned with the power sector's capability to withstand operational and physical consequences of disruptions (Macmillan, et al., 2022). The first formal definition of resilience, articulated by Holling in 1973, describes a resilient system as one that can absorb shocks and sustain the same relationships between variables even when confronted with a disruption (Holling, 1973). It's important to note that risk managers should not be misled into believing that stability automatically equates to resilience or that the absence of threats or hazards implies resilience. As a result, a resilient system is one that takes proactive measures to address new hazards (Macmillan, et al., 2022).

There are four primary stages involved in the risk assessment process of a power system, as defined by the Health and Safety Authority back in 2014. These stages include identifying any potential hazards, evaluating the risks that are associated with those hazards, implementing measures to control those risks, and analyzing the effectiveness of the measures taken (Yucesan and Kahraman, 2019; Celik and Gul, 2021). Risks can also be classified based on their types which may include technical risks, resource risks, policy and regulatory risks, economic and financial risks, social risks, and environmental risks. Identifying hazards is a comprehensive process that involves thoroughly studying all the possible hazards. These hazards can be categorized into anthropogenic hazards like feedback failure, lack of planning and management, and lack of maintenance, or natural hazards such as intense flooding, weirs formed by landslides, lightning, rapid snowmelt, and earthquakes (Badr, et al., 2023; Wang, et al., 2023). After identifying the risks, the next step is to analyze them to determine their likelihood and consequence and then prioritize them during the evaluation phase to assess their acceptability. The treatment stage involves implementing controls to mitigate the risks based on the outputs obtained from the evaluation stage (Abba, et al., 2022).

In this paper, the concept of energy hybridization is examined, particularly in the context of integrating different renewable energy sources with energy storage to enhance overall system resilience and minimize the risk of power outages. Section 2 provides an in-depth exploration of various renewable energy sources and energy storage options, assessing their strengths and anticipating future challenges. The third section delves into the concept of hybridization, exploring different configurations between these systems. Finally, the fourth section suggests power system capabilities as a strategy to mitigate the challenges introduced earlier.

2. Renewable Energy Systems

The shift from non-renewable to renewable energy sources has become an unavoidable reality, particularly with the rise in fossil fuel prices. Additionally, on a global scale, there is a growing environmental initiative (i.e., the Kyoto Protocol) advocating for this transition in response to the escalating natural hazards attributed to the effects of global warming. Consequently, the future agenda involves the construction of smart homes powered by renewable energy sources (Namvar and Salehi, 2024). The shift is evident in China, where the proportion of conventional thermal power has decreased by 20%, offset by a 23% increase in the share of renewable energy from 2014 to 2023, in which the installed capacity of renewable energy sources accounts for 32% (Zhou, et al., 2024). Looking at the broader European Union context, inclusive of the UK and Norway, the installed capacity of renewable energy stands at 33%, demonstrating a 12% growth from 2010 to 2019 (Brás, et al., 2023).

2.1. Resources

Over the last twenty years, the global installed capacity for wind generation, including both onshore and offshore setups, has seen a remarkable increase. According to IRENA's data, it has surged from 7.5 GW in 1997 to about 733 GW by 2018, marking a 98-fold expansion (IRENA, 2022). Wind power holds a substantial portion of the growing market among various renewable energy sources, particularly in Northern Europe (Østergaard, et al., 2023). According to the research conducted by Khalid et al., a notable advantage of wind power is that a significant proportion of its components, approximately 80–85%, can be recycled. However, it is noteworthy that the recycling process encounters challenges, particularly with the blades (Khalid, et al., 2023). The effectiveness of wind turbines is significantly influenced by wind speed. The system is susceptible not only to intermittent performance during low wind speed periods, but also to vulnerability in the face of extremely high wind speeds, prompting operators to potentially shut down the wind turbine to prevent damage (Modaberi, et al., 2023; Hassan, et al., 2023). In general, a wind turbine comprises a tower, blades, and a nacelle, along with transmission and distribution components. Failure to shut down or secure the system during windstorms may result in damage to these components. Additionally, in the event of breakdowns, the maintenance and repair of mechanical parts can extend up to 12 days, presenting a drawback due to extended system downtime. Furthermore, various electrical components are prone to failures, increasing the system's vulnerability. These electrical components are not only at risk during severe weather events but can also be susceptible to cyberattacks, potentially leading to the entire system's failure. This underscores the significance of evaluating and fortifying the resilience of the wind power system (Modaberi, et al., 2023).

Solar energy holds significant potential for electricity generation. Electricity can be produced directly from solar energy using photovoltaic panels or indirectly through fuel production, achieved by either reducing carbon dioxide to generate hydrocarbons or electrolyzing water to produce hydrogen (Somoye, 2023). The performance of photovoltaic (PV) systems is a topic of debate from various perspectives. The PV system may face various disruptions resulting in supplied power being insufficient to meet demand (Temiz and Dincer, 2023). Primarily, temperature rise can lead to a notable decrease in power efficiency, prompting the development of alternative systems like immersed water panels and solar photovoltaic thermoelectric systems (Brás, et al., 2023; Dada and Popoola, 2023). Moreover, other alternative systems such as the floating tracking concentrating cooling can address the issue of elevated temperatures while simultaneously enhancing energy capture by the addition of tracking systems (Dada and Popoola, 2023). The performance may also be hindered by dust and dirt, where the application of advanced cleaning methods and self-cleaning coatings can serve as effective solutions (El-Mahallawi, et al., 2022). Other approaches aim to resolve intermittency challenges and decrease the relatively high cost of solar energy compared to fossil fuels. This involves implementing energy storage systems or connecting solar installations to the grid system (Dada and Popoola, 2023; Temiz and Dincer, 2023). In conclusion, evaluating the resilience of the photovoltaic system is necessary in the face of disruptions caused by unstable weather conditions, leading to intermittency or reduced system performance. This assessment should also consider the trade-off between the cost of adding additional components and the percentage of improvement in power efficiency disruptions (Dada and Popoola, 2023).

Hydropower stands as a widely favored renewable energy source for its low cost and high predictability, contributing 62% to the global electricity generated from various renewable sources (Borba, et al., 2023). In China, it holds a substantial position among other renewable energy sources, accounting for 60% of electricity production in 2022 (Zhou, et al., 2024). Likewise, hydropower plays a vital role in Brazil, constituting 63% of electricity production in 2022, encompassing both renewable and non-renewable energy sources (Ember, 2023). Moreover, to attain electrification in Africa while concurrently reducing carbon emissions, the continent is likely to persist in extending the hydropower projects (Cáceres, et al., 2022). Hydropower's effectiveness hinges on the volume and strength of water flow, a factor influenced by precipitation levels (Somoye, 2023; Yang, et al., 2022). On that account, like other energy sources, it is susceptible to the impacts of seasonal weather changes and anticipated droughts (Yang, et al., 2022). Strengthening the system's resilience is possible through specific measures, such as the installation of orifices and low-capacity turbines. These additions enable the system to operate efficiently, even in conditions of low flow rates (Mujjuni, et al., 2023). Furthermore, additional measures at the regional level could be implemented, such as integrating various hydropower plants to complement each other. In other words, power plants operating at maximum capacity can compensate for supply shortages in regions disturbed by adverse weather conditions (Cáceres, et al., 2022). From a different perspective, hydropower's predictability and stability make it a strong candidate for hybridization with other renewable energy sources, creating a mutually beneficial situation. The reliability of hydropower positions it as a resilient partner to integrate with intermittent renewable sources, contributing to grid stability (Dallison and Patil, 2023). However, analyzing various renewable energy types based on the specific scenario of each case is crucial for the selection of systems that can complement hydropower in arid conditions (Borba, et al., 2023).

2.2. Energy Storage Systems (ESS)

The energy system's resilience and frequent intermittency of renewable energy can be resolved by implementing an energy storage system. The effect of a storage system is particularly significant, especially in emergencies (Modaberi, et al., 2023). Choosing the convenient energy storage system necessitates a distinct assessment for each scenario, considering project priorities and goals such as usage duration, cost, environmental impact, and efficiency. In general, the prevalent classification for energy storage systems is centered on usage duration, distinguishing between short-duration options like rechargeable batteries and thermal storage, and long-duration options such as compressed air energy storage (CAES), pumped hydro storage (PHS), or hydrogen storage (Temiz and Dincer, 2023; Ouedraogo, et al., 2023).

Energy storage, specifically using batteries, has been closely linked to our daily lives, especially in the last 15 years (Bonilla and Le, 2023). Batteries can be connected to both the grid and local renewable energy sources, offering a partially effective solution during disruptions caused by natural hazards (Macmillan, et al., 2022). Batteries are also regarded as a mature technology, driven by the continual development and reduction in the cost of lithium-ion batteries (Bonilla and Le, 2023; Trapani, et al., 2024). However, it may not be the most optimal choice for long-term storage or achieving competitive pricing. Additionally, there are debates about the environmental impact of batteries, attributed to challenges in disposal and recycling (Trapani, et al., 2024).

Two commercially viable options for scalable grid-level power output are compressed air energy storage (CAES) and pumped hydro storage (PHS). These methods offer cost-effective bulk energy storage, exceeding 100 MW, making them pivotal for achieving a complete transition to renewable energy when compared to alternative conventional technologies (Ouedraogo, et al., 2023; Javed, et al., 2020). While CAES might operate within manmade containers, providing partial flexibility in geographical location, PHS, despite its full geographical limitations, enjoys widespread acceptance globally (Modu, et al., 2023). With over 127 GW total capacity in hundreds of PHS plants worldwide, it outperforms CAES (Javed, et al., 2020). This significant capacity can be attributed to the higher efficiency of PHS, standing at 80% compared to CAES that accounts for only 60% efficiency. However, it is essential to recognize that PHS projects are categorized as mega projects, demanding a full detailed risk assessment to prevent any potential catastrophic failures. This fact underscores why the construction of such projects undergoes a thorough and lengthy process, typically positioning them in remote locations. Integrating pumped hydro storage projects with various renewable energy sources, such as wind and solar, facilitates sustainable energy management (Ouedraogo, et al., 2023).

Hydrogen storage is becoming increasingly prominent as a modern and advanced approach to energy storage, attracting notable attention. Hydrogen, known for its lightweight and high energy density ranging between 120-142 MJ/Kg, competes directly with fossil fuels (Nasser, et al., 2022). Another notable advantage is its potential for eco-friendly production from renewable sources, significantly contributing to the recent surge in interest in hydrogen. Despite the long-standing awareness of hydrogen production technologies, which were previously derived through polluting methods from other fossil fuels with low conversion efficiency, the renewed emphasis on environmental impact has fueled the current research trend (Li, et al., 2024). When compared to battery technology, hydrogen storage system outperforms in various aspects, including a longer lifespan, higher storage capacity without self-discharging issues, and greater tolerance to varying temperatures (Trapani, et al., 2024). This positions hydrogen as a highly competing candidate in the pursuit of decarbonizing heavy industries (Nasser and Hassan, 2023). This is because green hydrogen can now be generated through an electrochemical process using solar or wind energy. The electrochemical process involves feeding water into an electrolyzer, where water is split into oxygen and hydrogen (Nasser, et al., 2022; Li, et al., 2024). Despite its apparent simplicity, this technology still encounters some challenges as it requires a high amount of energy for both the reaction and the kinetic obstacles. These kinetic obstacles are observed in the form of hindered electron transport and the accumulation of bubbles on the electrode surface (Li, et al., 2024). In addition, hydrogen, being a highly flammable substance, is still undergoing continuous testing and research to ensure safe handling and storage (Nasser, et al., 2022). Despite that, it can still shape the road for carrying out a stand-alone renewable energy off-grid project that can solve the intermittency issue of solar and wind energy (Nasser, et al., 2022).

3. Renewable Energy Systems hybridization

The utilization of multiple renewable energy systems can offer a practical solution for meeting energy demands while reducing pollution. These systems can support each other in times of outages. The development of hybrid systems depends on crucial factors that balance cost and effectiveness (León Gómez, et al., 2023). Hybrid systems refer to the combination of multiple-generation technologies that are more cost-effective and valuable when coupled together as compared to using them independently as stand-alone technologies (Lee, et al., 2020). This paper categorizes hybrid systems as binary systems with an energy storage technology.

3.1. Binary system with pumped hydro-storage

One example of binary hybrid systems involves combining wind and hydro energy. In Brazil, a study was conducted to assess the potential of integrating offshore wind energy with hydropower. Brazil primarily produces electricity through hydropower, but during the dry season, the power generated from hydropower is insufficient to meet demand. This necessitates a balance with fossil fuel generators, which results in significant emissions. The study found that offshore wind energy could be integrated with hydropower to provide the required energy, significantly reducing the need for fossil fuels, and reducing emissions by up to 97%. Additionally, offshore wind energy can be used for energy storage during the rainy season by pumping and storing water in the reservoirs. However, since offshore wind energy will mainly be directed towards energy storage, natural gas may still be used on a reduced scale during the rainy season (Borba, et al., 2023).

Numerous studies have proposed the combination of photovoltaic solar energy and hydropower (Lee, et al., 2020; Li, et al., 2021; Quaranta, et al., 2023). This type of hybridization offers benefits on both a seasonal and a daily scale. During the dry season, when precipitation levels are low, the peak of solar irradiance can be observed. Meanwhile, the maximum efficiency of hydropower can be observed during the rainy season when solar irradiance is low. As a result, the two systems can complement each other, with solar power being relied upon during the dry season and hydropower being relied upon during the rainy season (Lee, et al., 2020; Quaranta, et al., 2023). Any excess solar energy can be directed towards energy storage. On a daily scale, hydropower can provide a solution to the intermittency of solar power during the night. Furthermore, both systems can utilize the same transmission infrastructure, leading to savings in transmission costs (Lee, et al., 2020). A cutting-edge topic in the literature is the combination of Floating Solar Photovoltaics (FPV) with hydropower, where the PV panels float above the reservoir or dam water (Lee, et al., 2020; Sanchez, et al., 2021). Portugal has already implemented the world's first project utilizing this technology (Lee, et al., 2020). Compared to conventional hybridization methods, this solution offers several advantages, including reduced land usage and decreased evaporation rates of dam water used for power generation (Lee, et al., 2020; Sanchez, et al., 2021). Research conducted by Sanchez et al. concentrated on Africa, reveals that the electricity output can be boosted up to 58% by covering just 1% of the hydropower reservoir. The study recommends the integration of this technology while extending hydropower projects, as it can effortlessly enhance the power capacity of the system (Sanchez, et al., 2021).

3.2. Binary system with battery storage

Utilizing a hybrid system of offshore wind and wave power is an environmentally favorable option, as it involves increased use of natural resources and reduced impacts associated with onshore wind facilities (Charles

Rajesh Kumar, et al., 2021; Hu, et al., 2020). Although wave energy is more consistent and intense than wind energy, it is still in a relatively early stage of development. Offshore wind energy is rapidly evolving due to the stronger and more consistent winds at sea, as well as the availability of sufficient space for wind farm installation. The combination of wind and wave energy in a hybrid system can diminish the hours of zero production compared to a standalone wind turbine due to the persistence of ocean waves (Charles Rajesh Kumar, et al., 2021). However, the high expenses associated with design, installation, operation, and maintenance present significant challenges to the deployment of wind and wave energy in deep water offshore locations (Hu, et al., 2020).

Solar and wind energy stand out as prime examples of standalone systems, offering potential integration for a more robust hybrid system. Both systems bring unique benefits that can be strategically combined for optimal results. The simplicity of installation and low maintenance associated with solar energy complements the continuous and cost-effective nature of wind energy, particularly on a larger scale (Hemeida, et al., 2020). Harnessing wind energy during the entire day, including nights without solar availability, becomes feasible. The hybridization of these systems, coupled with energy storage solutions such as batteries, meets diverse consumer energy needs (Hassan, et al., 2023; Hemeida, et al., 2020). This integrated approach not only ensures a steady energy supply but also reduces the risk of electricity outages during extreme weather events. The variation in energy sources, supported by a storage system, enhances resilience (Hassan, et al., 2023). Notably, an Egyptian study conducted in a region with abundant solar irradiation and high wind speeds in the eastern part of Egypt demonstrated the economic success of this hybrid system (Hemeida, et al., 2020).

3.3. Binary system with hydrogen storage

Photovoltaic or wind energy can be used to produce hydrogen, which is an effective way to accelerate the transition towards renewable energy. It can be an effective solution for the intermittency problem due to unstable weather conditions. In terms of cost, hydrogen production through wind energy is the preferred method (Nasser and Hassan, 2023; Messaoudi, et al., 2024). Recent studies have shown that off-shore wind energy is more attractive than on-shore wind energy due to its higher capacity factor (Komorowska, et al., 2023). Integrating wind turbines with electrolyzers in the island of Flores in Portugal has proven to be an effective way to reduce diesel consumption by 76% (Trapani, et al., 2024). To implement this project, it is important to estimate the potential amount of hydrogen that can be produced from the wind map of the desired location (Messaoudi, et al., 2024). According to a study conducted in Norway, the most economical design for renewable energy systems (RES) involves integrating renewable electricity generation from photovoltaic (PV) solar panels and wind turbines with hydrogen-based energy storage. The incorporation of a hydrogen system serves two key purposes: first, it prevents the oversizing of the PV-wind system by ensuring electricity generation matches actual demand, and second, it reduces the reliance on extensive battery installations. The hydrogen storage component efficiently stores surplus energy generated during peak production periods, offering a balanced and flexible storage solution (Trapani, et al., 2024).

4. Power system capabilities

The prospect of power absence, with its consequential losses, becomes unacceptable under any circumstances. In Pakistan, a power outage resulting from frequency instability led to a blackout impacting 90% of the population (Masood, 2021). Power disruptions can stem from both manmade events and natural disasters. Different threats to the renewable energy system have been illustrated in Fig. 1 including natural disasters, dynamic weather conditions, inefficient energy storage, system complexity, lack of maintenance, lack of management, and cyber-attack. Surveys indicate that the primary threat to power systems arises from natural disasters, often referred to as high-impact, low-probability events (HILP) (Xu, et al., 2023). These events can result in severe consequences, causing significant disruptions to equipment and infrastructure (Modaberi, et al., 2023). For example, the severe ice storm in Texas in 2021 led to a power crisis, with natural gas transmission pipelines blocked by ice and wind turbine blades freezing. Additionally, Hurricane Maria in 2017 damaged a wind farm with 13 turbines and a solar farm in Puerto Rico (Xu, et al., 2023). High-impact low-probability events encompass not only storms and hurricanes but also floods, earthquakes, avalanches, wildfires, and lightning. Consequently, the resilience of the power system has become a critical concern, tested across three phases: pre-disturbance, during the disturbance, and post-disturbance. The resilience measures are classified as proactive, active, and reactive, depending on the system phase during exposure to the disturbance. Subsequently, the most cost-effective measures are selected and implemented to enhance the resilience of the power system (Modaberi, et al., 2023).

Fig. 1. Renewable energy power system challenges.

Proactive measures aimed at enhancing system resilience before a disturbance include the following:

- In the face of potential natural hazard threats, it is crucial to develop fragility curves for energy system components tailored to each specific acute weather event scenario. These curves play a valuable role in energy system modelling, enabling the incorporation of failure probabilities into energy management studies for more accurate results (Macmillan, et al., 2022).
- In flood-prone areas, it is possible to design energy system equipment and infrastructure to be situated or moved to elevated regions above flood levels. This helps prevent any minor damage that could otherwise impact the entire system (Castro, et al., 2023).
- Additional protective measures for the power system against natural hazards include reinforcing distribution lines and, or if necessary, burying them underground (Castro, et al., 2023; Dehghan, et al., 2023).
- Deploying a hybrid energy storage system, especially in off-grid scenarios, to enable the utilization of resilience features like redundancy and robustness (Dehghan, et al., 2023; Modu, et al., 2023; Cárdenas Oyarzún, 2023).
- The reconfiguration of renewable energy networks to withstand disturbances and boost resilience can be achieved by incorporating virtual power plants (VPP) and microgrids (MGs). The case in Japan illustrates the substantial benefits of such measures against technical, manmade, and natural hazards (Dehghan, et al., 2023; Yokoyama, 2022).
- Reinforcing structures and fortifying PV panels, especially in regions with a higher probability of storms and typhoons, proves to be a cost-effective strategy for enhancing resilience (Castro, et al., 2023).
- Reviewing the weather forecast to receive early notifications of any disruptions and applying preventive measures as soon as possible (Modaberi, et al., 2023).
- Developing an offline restorative plan that can be used after the disturbance (Modaberi, et al., 2023).

The corrective or active measures that can be implied during the disturbance include the following:

- Reconfiguration of the power network with the possibility of enabling the microgrid islanding mode and the usage of backups if required (Bhusal, et al., 2020).
- Improving system stability by integrating essential components such as quick-acting automatic voltage regulators and power system stabilizers (Gui, et al., 2023).
- Mitigate the power disturbances by using mobile energy resources such as combustible fuel generators that can run on biofuels or using mobile energy storage (Bhusal, et al., 2020).
- Developing an active detection approach in the case of wind farms utilizing a rotor speed observer/estimator to uncover and recognize false data injection (FDI) attacks (Modaberi, et al., 2023).

The restorative or reactive measures that can be applied after the disturbance include the following:

- Improving system stability using high-speed circuit breakers with automatic reclosing schemes. It proves to be useful during transient events such as momentary lightning strikes (Gui, et al., 2023).
- Giving precedence to the restoration of critical loads by taking into account the cost of customer interruptions (Modaberi, et al., 2023).

5. Conclusion

The power system is a critical component in every country, and any adverse impact could result in significant losses. Therefore, this paper examines the resilience of the power system when faced with diverse hazards, including anthropogenic and natural threats. The focus is on renewable power systems, specifically exploring the concept of hybridization as a solution to vulnerabilities, where two complementary hybridized systems are proposed. The paper suggests hybridizing two renewable energy sources with the support of an energy storage system. Examples include the promising combination of wind and hydro energy in Brazil, and solar and hydro energy with great potential in Africa. Additional examples involve offshore wind with wave energy and the combination of wind and solar energy, which can complement each other when paired with a battery source in suitable regions. Notably, eastern Egypt serves as an excellent example of hybridizing both wind and solar energy due to their year-round abundance. These latter examples can also incorporate hydrogen storage on a large scale. The paper presents a comprehensive framework for enhancing the resilience of renewable energy systems, taking into account various risk factors and proposing proactive, active, and reactive measures to address challenges and ensure a sustainable and reliable power supply. The challenges posed by the proposed solutions can be observed through a detailed study that includes effective design tailored to each situation, achieving a balance between additional costs and the benefits acquired from reducing the possibility of risks.

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