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Methodology for wind farms critical infrastructure network safety and resilience to climate change analysis

Keywords

critical infrastructure, wind farm, network, offshore, climate change, resilience

Abstract

The paper explores the terminology, which refer to wind farms critical infrastructure network. Moreover, there are presented definitions of wind farm critical infrastructure network interconnections and interactions within the Baltic Sea region. The impact of changing climate/weather conditions on the critical infrastructure and its operation are also considered.

1. Introduction

To ensure compatibility in this paper and across the next papers concerned with this topic, the common "working terminology" should be fixed. Offshore wind energy is the fastest growing energy sector. But this also a great challenge for developers, statutory regulators including economy, environment and maritime administration. This is because of the fact that offshore wind farms create artificial islands and will exclude large parts of the see territory from navigation, fishery and recreation and may interfere with other legitimate users of the sea, including offshore oil and gas industry, cable and pipeline networks as well as other seabed exploitation. This article will show wind farm critical infrastructure network taxonomy. From the ecological point of view all mentioned infrastructure networks create the impact accumulation at the given area [11]. According to [11], there are several energy associations in the countries surrounding the Baltic Sea, which implement the optimal solutions, innovative technologies and other services protecting the wind farms networks:

- *German Wind Energy Association* (GWEA) - the largest renewable energy association in the world. They include wind turbine manufacturers, operators and their shareholders, planning offices, financial institutes, scientists, engineers, technicians and lawyers, but also early conservationists, schoolchildren and students. Its strength lies in its structure, as it represents a concentration of know-how and experience from the entire sector;
- *Danish Wind Industry Association* (DWIA)- an interest and industry association with more than 240 members across Denmark. DWIA's members consist of wind turbine manufacturers, energy companies and a wide range of companies that provide components, services and consultancy. DWIA manages the interests of the members and creates a framework for the various forums, in which members can utilize the potential in knowledge sharing and experience exchange with players within and outside the industry. Furthermore, DWIA promotes the member interests on both the national and international political stage;
- *Polish Offshore Wind Energy Society* (POWES) - society registered in 1997 as one of the first organizations that promote the development of offshore wind energy. Its main goal is to support the offshore wind energy sector in Poland and to promote an economic development that is favourable for offshore wind energy, using innovative technologies and respecting the need for environmental protection;

- *Polish Wind Energy Association* (PWEA) - a non-governmental organization supporting and promoting the development of wind energy from 1999. It brings together the most important companies in the wind energy market in Poland, as well as investors and producers of turbines and power components, both from Poland and other countries;
- *Lithuanian Wind Energy Association* (LWEA) - established in 2002, it is attempting to assure the most favourable conditions for the development of wind energy projects, including fair legislation and an attractive business environment. Some of the major objectives are to strive for decentralization of the national energy market, to achieve energy independence through the development of wind energy and to pursue the implementation of the EU's renewable energy policy;
- *Maritime Transmission Infrastructure of Electricity* (MTIE) - a project that can accumulate with the impact of the planned OWF Baltic II. The energy generated by the OWF BSII (and the planned at an earlier date OWF BSIII) will be sent ashore via export cables. They will not be a part of the farm, but a separate project called the Maritime Transmission Infrastructure of Electricity (MTI BSIII), which is owned by Polenergia III, with the head office in Warsaw. For MTI BSIII locational licenses have been issued for laying submarine cables in the EEZ and territorial waters of the Republic of Poland. In addition, in 2014 the Investor acquired a decision for determining the scope of the EIA report for the project;
- *Swedish Wind Power Association* (SWPA) - a collective trade organization for private persons, wind turbine owners and wind power developers. The association has approximately 2,000 members and is active both in Sweden and internationally. It promotes the development of wind power through mediating knowledge, promoting technical development, creating reasonable economic and financial conditions, and collaborating with authorities, organizations and the industry;
- *World Wind Energy Association* (WWEA) - founded 2001 in Denmark, represents the wind power sector worldwide.

2. State of art

Before the considerations on critical infrastructure at Baltic Sea Region taxonomy, we refer to definitions of selected basic notions concerned with critical infrastructures and climate and weather impacts on their safety included in the report [6].

At first, we have to define the terms concerned with critical infrastructures terminology. The *Baltic Sea infrastructure*, which is an industry and other system (e.g. drilling platforms, gas and oil pipelines, wind farms, telecommunication systems, waterways, maritime transport, ports with their intermodal connections), performing activities within the Baltic sea area. According to [10], *Energy infrastructure* is the total system of generation, transport, distribution, trade, supply and consumption of energy. This means not only the physical network (e.g. power plants, gas pipes, heat delivery stations), but also the social (economic and institutional) network that manages and controls the physical system. Together, these networks form a *socio-technical infrastructure system*. It is a complex system; the technological, economic, and institutional domains are strongly interdependent. Those systems used to trade energy commodities are called *energy trading systems* [5]. They differ from the *electrical power systems*, a critical infrastructure characterized by generation stations, transmission and distribution networks that create and supply electricity to end-users so that end-users achieve and maintain nominal functionality, including the transportation and storage of fuel essential to that system [14].

The *transmission* according to [5] is defined as a passage through sub-stations within country and between country interconnectors. It is possible through *distribution grids* (low-voltage) and *sub transmission grids* [9]. *Distribution grids* are radial networks that carry the electric power from the higher voltage levels to the final users. The number of levels in a distribution grid depends upon the density and magnitude of demand and the terrain. *The sub transmission grids* (or *regional grids*) are radial or locally meshed networks connected to the transmission grid via infeed points. Smaller generating plants (e.g. wind power stations and gas turbines), and large users are connected to these grids. *Offshore wind farm* is a group of wind turbines arranged in the same seabed location used to produce electricity [3].

2.1. Wind farms critical infrastructure network terminology

According to Cambridge Dictionary [3], the selected terms concerned with critical infrastructures are presented. *Wind farm* (*wind park*) is a group of wind turbines arranged in the same land location used to produce electricity. It differs in structural way from the *offshore wind farms* defined in the State of Art.

The offshore wind farm critical infrastructure network is a term used when [1]:

- at least two wind farms use a common transformer station or a common cable exporting energy on land. *Power cables* are defined as subsea cables

which are used to either import or export power capacity. These cables are large diameter cables with similar characteristics and behaviour to the export cables associated with offshore wind farm developments. We distinguish two types of cables - *internal cables* (usually called *grids* or *inter-turbine array cables*), which are an integral part of the offshore wind farm; and *external cables* (*export cables*), which not necessarily need to be a part of the offshore wind farm. In Poland, the export cable of the offshore wind farms is called *Maritime Transmission Infrastructure* (MTI). The *inter-turbine array cables* are the cables which connect the offshore turbines into arrays and also connect the various arrays together. It is normal practice to cable several turbines together in an array, with each cable providing a link between two adjacent turbines. Each end of the cable is terminated onto the high voltage (HV) switchgear located within the turbine tower. These cables would also connect any offshore substation to the offshore WTG arrays. The cables between WTGs are relatively short in length (typically in the range 500m to 950m). However, the cables between the offshore substation and the WTG arrays could be longer and possibly up to 3 km. The function of the export cables is to transmit the electrical power from the offshore wind farm to the appropriate cable connection facility at the shoreline or landfall;
- two or more offshore wind farms use the same connection on land (*onshore substation*);
- two or more offshore wind farms have the same operator;
- two or more offshore wind farms benefit from the joint *operation centre*. A *control/operation centre* is a place from which a system is centrally monitored, regulated, and directed, or in which operational devices and controls are housed [13].

Wind turbines are used to produce power to make electricity and have a tall structure with blades that are blown round by the wind. To supply electrical power to a large area, there is used a system of connected wires called *grids* (*Figure 1*). *Land power stations* (*power plants*) and *marine power stations* are places where electricity is produced, at the land and sea respectively [3]. The terminology of popular methods of anchoring offshore wind turbines on the sea bed or floating structures (i.e. gravity base, tripod, monopole, and jacket, combined jacket with a tower, spar buoy and semi-submersible) is illustrated in *Figure 2*.

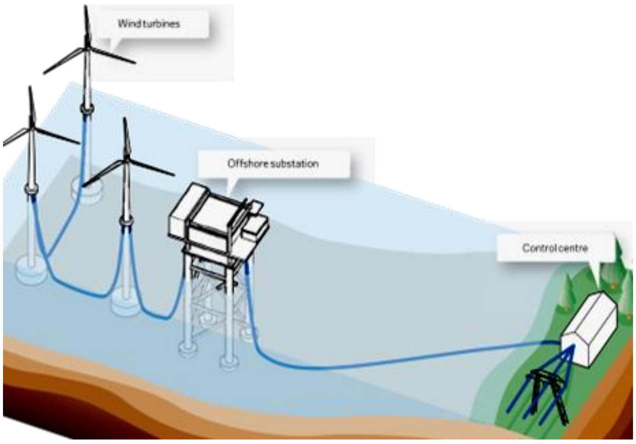

Figure 1. Offshore wind turbines connections through an internal grid to an offshore substation, a control centre and then to the grid [15]

Figure 2. Offshore floating wind turbines – methods of anchoring on the seabed and floating structures [2]

In the Baltic Sea Region, there is a *Baltic Wind Farm Critical Infrastructure Network* (BWFCIN) - the set of all current (future) energy production wind farms existing (planned) [7]. Offshore wind farms create *artificial islands*, which are defined as the man-made islands or other structures surrounded by or floating on water [13].

2.2. Climate change terminology

The offshore wind farms do not emit *greenhouse gases* (GHG), which are gases that causes the greenhouse effect, especially carbon dioxide. *Carbon emissions* (carbon dioxide and carbon monoxide) are usually made by things such as factories or cars that burn carbon and cause pollution [3]. In addition, they replace part of the *fossil fuel mix* (a fuel such as coal or oil that is obtained from under the ground) in the electricity generation on the spot markets, gaining from the *merit-order effect*. The merit order effect is the term used to describe the displacement of more expensive marginal cost thermal plant by wind or solar which has zero marginal cost [11].

Public support for offshore wind farms is generally high, particularly where evidence is presented through the formal consenting and consultation processes that developments are sited in an appropriate location, where environmental and negative economic effects are minimal or can be effectively managed [1].

2.3. Resilience terminology

Construction and operation of the offshore wind farm critical infrastructure network significantly affects:
- steamship;
- fisheries;
- recreational boats;
- other sea uses - oil and gas extraction, the aggregates exploitation, the excavated material deposition, etc.

In the case of Poland wind farms, we have to deal with four offshore wind farms with 1000 turbines, 1000 km of internal cables and 300 - 400 km of export cables. The maximum production capacity is nearly 5,000 MW, which is critical from the point of view of the state interests. For the construction and operation of all these wind turbines, there is a need of dozens of specialized vessels operation. That will perform 10,000 cruises a year across the highly frequented shipping lanes through which flows a year almost 20,000 ships. The number of visits in small ports, i.e.: Łeba or Ustka can increase 100 times. In order for this to work reliably, there is a need to use:

- Navigation marking plan
- Navigation warning plan
- Safe passage plan – vessel traffic services
- Emergency passage plan
- SAR plan
- Pollution response plan.

From the point of view of reliability and security, the most sensitive element of the wind farm critical infrastructure are the export cables (10% of investment costs, 80% failure). Polish-Swedish cable *SwePol Link* has an average of two crashes per year, most often caused by fishermen. Switching off one, two or even ten turbines is not a problem. Switching off one cable can cause a decline in production and switching of from 50% to 100% of turbines. Therefore, the cables should be laid deeper and more frequently. Protection and reliability of the export cable is the most important.

In order to allow a comprehensive review of the various cable burial machines, and to be able to investigate the environmental effects associated with each machine, four categories have been established for the cable burial machines [1]:

- *Cable burial ploughs* – passive tools towed from a host vessel. The plough share cuts a wedge of soil which is then lifted by the action of the plough cutting through the seabed;
- *Tracked cable burial machines* - vehicles usually operated in post laid burial mode to bury subsea cables which have been previously laid on the seabed and are typically used for shorter sections of cable burial. A *jetting system* works by fluidising the seabed using a combination of high-flow, low pressure and low flow high pressure water jets to cut into sands, gravels and low to medium strength clays. Progress in clays is dictated by the available power budget to the tracked cable burial vehicle and the level of cohesion in the clay. *Mechanical rock wheel cutters* can also be fitted to tracked cable burial vehicles and, as the name suggests, are used to cut narrow trenches into hard or rocky seabed typically operating in the 1.5m trench depth range. *Mechanical chain excavators* are typically used in circumstances where the seabed material is beyond the capability of a jetting system or where deeper burial is required;
- *Free swimming* ROVs *(Remotely Operated Vehicles) with cable burial capability* - use thrusters for propulsion and manoeuvrability and are equipped with a work package or work skid for intervention tasks or cable burial operations;
- *Burial sleds* - developed for the burial of the shore end section of cable systems and work in shallow water. As well as being used for open water shore end cable installation, these machines are often used for river crossing and estuary cable work.

Cable burial and other protection measures are used to ensure cables are adequately protected from all forms of hostile seabed intervention. Cable burial is the primary method for protecting subsea cables [1]. Providing the correct burial machine is selected for the designated burial task, the target depth of burial is likely to be achieved. If a cable is not adequately protected, damage can and will occur. In certain locations, highly specialist cable burial techniques have been developed to suit the exacting requirements of that particular location. The offshore wind farm industry has generally recognized that the main risks posed to the subsea cables derives largely from inshore fishing activity and dragging anchors from coastal vessel traffic [1].

Offshore windmills do not operate when the wind speed is less than 5m/s and above 30m/s. Windmills have to be turned off when any threat is expected, such as a drifting ship. There should be carried out rescue operations, performed service or repair, the transformer station, the internal network cable or the export cable may be damaged, etc.

3. Wind farms critical infrastructure network at Baltic Sea region taxonomy

3.1. Wind farms critical infrastructure network taxonomy

At present, there are 13 offshore wind farms in the Baltic Sea, situated in Denmark, Germany, Sweden and Finland with a total capacity of about 436 MW. There are plans for 29 new offshore wind farms in the region until 2020 [16]. Wind power is a renewable energy source and as such, something that is supported by WWF and by the wider society. The energy produced by the wind farms is called *renewable energy*, because it comes from a source that is not depleted when used, such as wind or solar power [13].

E.ON is a European holding company committed to the sustainable implementation of offshore wind energy by actively supporting research and development of suitable solutions to mitigate the impacts on ecosystems. As part of the consenting process, an *Environmental Impact Assessment* (EIA) is carried out to evaluate possible impacts of an offshore project on the marine ecology [4].

The main terms used in offshore wind farm infrastructure installation are presented below:

- *Array cable(s)* - generic term collectively used for Inter Turbine Cables and Collector Cables. See also Infield Cables;
- *Barge* - a non-propelled vessel commonly used to carry cargo or equipment. (For the purposes of this document, the term Barge can be considered to include Pontoon, Ship or Vessel where appropriate);
- *Cable burial* - a submarine power cable is trenched into the seabed and covered with soil providing complete burial of a cable (see Cable Trenching below);
- *Cable grips* - cable grips are used to pull or support cables and pipes. They work on the principle of the harder the pull, the tighter the grip;
- *Cable trenching* - a submarine cable is lowered beneath the mean seabed level into an open cut trench. The trench is left open and any subsequent cover of the cable is by natural reinstatement of the seabed;
- *Export cable(s)* - submarine power cables connecting the offshore wind farm transformer station to a landfall connection point;
- *Inter turbine cables* - submarine power cables connecting two turbines. A series of inter turbine cables form an array cable. Also known as *intra array cables*;
- *Intra array cables* - submarine power cables connecting two turbines. A series of intra array cables form an array cable. Also known as Inter Turbine Cables;
- *Infield cables* or *infield array cables* - submarine power cables connecting two offshore wind turbines or an offshore wind turbine and the offshore substations or the offshore transformer station;
- *J-tube* - a J shaped tube fitted to offshore structures to install submarine cables between the seabed and the structure topsides;
- *Monopile* - common tubular structure used as foundation for offshore wind turbine generator.
- *Nacelle* - the part of the wind turbine on top of the tower, where the hub, gearbox, generator and control systems are located;
- *Non destructive testing* - ultrasonic scanning, magnetic particle inspection, eddy current inspection or radiographic imaging or similar. May include visual inspection.
- *Net weight* - the calculated or weighed weight of a structure, with no contingency or weighing allowance;
- *Offshore converter station* - the offshore converter station transforms the collected energy from the offshore transformer stations (several wind parks) to Direct Current in order to send it to a land based converter station;
- *Offshore transformer station* - the offshore transformer station is transforming the collected energy from the wind turbines to a higher voltage;
- *Operation duration* - the planned duration of the operation from the forecast prior to the Point of No Return to a condition when the operations / structures can safely withstand a seasonal design storm (also termed "safe to safe" duration); this excludes the contingency period;
- *Operation*, *marine operation* - any activity, including load-out, transportation, offload or installation, which is subject to the potential hazards of weather, tides, marine equipment and the marine environment;
- *Operational reference period* - the operation duration, plus the contingency period;
- *Point of no return* - the last point in time, or a geographical point along a route, at which an operation could be aborted and returned to a safe condition;
- *Route clearance* - the use of grapnels and other methods to clear debris from the planned cable routes. Normally done well in advance of cable operations to allow adequate time to remove debris;
- *Rotor* - configuration consisting of the complete set of blades, connected to the hub;
- *Scour pit* - the result of scour around a pile, leg etc.;

- *Shore End* - the section of submarine cable installed between the landfall connection point and the offshore set up position of the CLV or CLB;
- *Sea fastenings* - the system used to attach a structure to a barge or vessel for transportation;
- *Simultaneous Operations* - operations usually involving various parties and vessels requiring co-ordination and definitions of responsibilities;
- *Tower* - the tubular element from the top of the flange on the foundation to the bottom of the flange below the nacelle, generally built up of several sections;
- *Transition Piece* - a tubular structure on top of a monopile to provide a horizontal foundation for the tower;
- *Weather restricted operation* - a marine operation which can be completed within the limits of an operational reference period with a weather forecast not exceeding the operational criteria. The operational reference period (which includes contingencies) is generally less than 72 hours. The design environmental condition need not reflect the statistical extremes for the area and season;
- *Weather unrestricted operation* - an operation with an operational reference period greater than the reliable limits of a weather forecast. The operational reference period (which includes contingencies) is generally more than 72 hours. The design weather conditions must reflect the statistical extremes for the area and season.

3.2. Resilience taxonomy

According to [12], the *risk* is the combination of the frequency and severity of the consequences of the event. Assessing the risk facing the wind farms critical infrastructure networks, there are distinguished *individual risk* or *social risk*. The first one is a direct measure of the frequency of incidents of death for individuals. The latest one is indirect measure of the scale of the incident, taking into account the public aversion to major accidents. The potential threat to human life, health, property and the natural environment is called *hazard*. *Initiating event* is the first event in the sequence leading to a hazardous situation or accident. Proper risk management and risk control can help identify potential problems, hazards and threats and respond to the risks that critical infrastructures are exposed to. *Means of risk control* are means for control of a single element of risk, while *option of risk control* means grouping of risk control measures to form a practical recommendation for lowering the risk level. One way of ensuring that action is taken before a disaster occurs is the use a process known as *Formal Safety Assessment* (*FSA*). It is a rational and systematic process of assessing the risks of an activity that allows to assess the costs and benefits resulting from introducing the option to reduce the given risk.

Any *accident* (unintended event or injury resulting in victims, loss or destruction of property or environmental damage) close to wind farm area may force an emergency stop for the single turbine, the group of turbines or the whole wind park [7]. The *incident category* is categorizing the accident in accordance with its character. According to [12], there are distinguished possible marine accidents categories listed below:

- *Foundering* - sinking below the surface of the water;
- *Collision* - a vessel striking, or being struck, by another vessel, regardless of whether either vessel is under way, anchored or moored; but excludes hitting underwater wrecks;
- *Allision* - a violent contact between a vessel and a fixed structure (for the purpose of further elaboration a uniform, independent from energy term for collision has been assumed - contact);
- *Contact* - a vessel striking, or being struck, by an external object that is not another vessel or the sea bottom;
- *Fire* - the uncontrolled process of combustion characterized by heat or smoke or flame or any combination of these;
- *Explosion* - an uncontrolled release of energy which causes a pressure discontinuity or blast wave;
- *Loss of hull integrity* - the consequence of certain initiating events that result in damage to the external hull, or to internal structure and sub-division, such that any compartment or space within the hull is opened to the sea or to any other compartment or space;
- *Flooding* - sea water, or water ballast, entering a space, from which it should be excluded, in such a quantity that there is a possibility of loss of stability leading to capsizing or sinking of the vessel;
- *Grounding* - the ship coming to rest on, or riding across underwater features or objects, but where the vessel can be freed from the obstruction by lightning and/or assistance from another vessel (e.g. tug) or by floating off on the next tide;
- *Stranding* - the ship becoming fixed on an underwater feature or object such that the vessel cannot readily be moved by lightening, floating off or with assistance from other vessels (e.g. tugs). (For the purpose of further elaboration another term was also assumed – run aground);
- *Machinery related accidents* - any failure of equipment, plant and associated systems which

prevents, or could prevent if circumstances dictate, the ship from manoeuvring or being propelled or controlling its stability;

- *Payload related accidents* - include loss of stability due to cargo shifting and damage to the vessel's structure resulting from the method employed for loading or discharging the cargo. This category does not include incidents which can be categorized as Hazardous Substance, Fires, Explosions, Loss of Hull Integrity, Flooding accidents etc.;
- *Hazardous substance accidents* - emission of toxic flammable substances in the form of gas, vapour or dusts causing impairment of the health and/or functioning of people or damage to the vessel. The following can be the cause of emission: fire, accidental release, human error, failure of process equipment, loss of containment, or overheating of electrical equipment.
- *Accidents to personnel* - accidents which cause harm to any person on board the vessel e.g. crew, passengers, stevedores; which do not arise as a result of one of the other accident categories. Essentially, it refers to accidents to individuals, though this does not preclude multiple human casualties as a result of the same hazard, and typically includes harm caused by the movement of the vessel when underway, slips, trips, falls, electrocution and confined space accidents, food poisoning incidents, etc.;
- *Accidents to the general public* - accidents which lead to injury, death or loss of property amongst the population ashore resulting from one of the other ship accident categories;
- *Capsizing* - the overturning of a vessel after attaining negative stability.

According to [12], all of the listed above accidents categories may bring the *consequences* - the results of the accident. The *frequency of incidents* is defined as the number of events per unit of time, usually within one year.

4. Conclusions

In the paper the terminology and methodology on for wind farms critical infrastructure network are presented. More detailed description is given in the EU-Circle report [7].

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