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Adaptation Options and Decision-Support for Electricity Infrastructure Operators under Influence of Extreme Hydro-Meteorological Events

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Abstract Research showed that most of the so-called climate change adaptation “happens” more or less due to the fact that extreme weather has always had an impact on infrastructure and that regulations, standards and rules have been reviewed and updated regularly. Nevertheless, a possible shift in extreme weather events due to climate change needs to be considered in planning and construction of electricity infrastructure. Therefore, first of all an identification of the impacts of extreme hydro-meteorological events on electricity infrastructure takes place in this paper. Afterwards, some of the possible adaptation options, especially for thermal power plant cooling facilities, wind power plants and storage infrastructure, are highlighted. Identification and adaptation leads to a decision-support for power plant operators who have to deal with increased impacts due to shifting intensity and frequency of severe weather events.

Key words electricity infrastructure; climate change; extreme hydro-meteorological events; adaptation options

1. Introduction

In the widest sense, electricity infrastructure affected by extreme hydro-meteorological events can be counted into the concept of Natechs (natural disasters triggering technological accidents). This paper highlights some of the damages that can happen due to extreme hydro-meteorological events, or shorter, severe weather. Power plants and the connected infrastructure have always been subject to environmental influences. Since large sectors of publically used infrastructure, such as transport, IT, health and water supply depend on electricity, the energy infrastructure can also be entitled a critical infrastructure.

Thermal power plants (i. e. gas-, oil- and coal-fired as well as nuclear plants) are subject to shifts in cooling water supply. Cooling water supply is highly important as energy conversion via steam cycle needs about 100 litres of fresh water for cooling in order to generate a kilowatt-hour of electricity (Feeley III et al. 2008). Moreover, the energy industry requires a comprehensive approach for emergency

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planning in the case of extreme flood events (e.g. Schulz (Sieber née Schulz) 2011b). Some of the initial points of this approach are shown in the paper.

Renewable energies, on the other hand, are often vulnerable to the source they need for electricity generation. Hydropower plants are subject to high or low water levels, whereas wind power plants (masts and poles) are impacted by wind pressure during storms. Photovoltaic installations and panels are affected by almost all extreme events, hail stones cause cracking of the covering layer, storms can lead to tipping over, lightning may cause overvoltages and snow layers prevent full insolation.

The said vulnerabilities show that energy infrastructure, and especially electricity production and distribution, need to be adapted to changing environmental conditions. Thus, in chapter 2, extreme hydro-meteorological events and their impacts on electricity infrastructure are defined. Afterwards, chapter 3 covers some examples of adaptation options in the context of climate change. Chapter 4 consequently points to a planning process and decision-support for power plant operators by using Geographical Information Systems (GIS) for easy use on-site.

2. Definition and Classification of Hydro-Meteorological Extremes and their Impacts on Electricity Infrastructure

The definition of hydro-meteorological extremes can either be very general (rare, severe, rapidly occurring) or very precise by using thresholds of the describing parameter and the occurrence probability. In this context, extreme hydro-meteorological events are categorised into four groups and differentiated by parameters as outlined below. Table 1 contains the thresholds used in this paper. These are:

i. Temperature-related events can be best defined by the occurrence of daily maximum or minimum air temperatures. For heat and summer days the following thresholds apply: air temperatures of greater than 25 °C are counted as summer days and as soon as the maximum temperature is greater than 30 °C a day is labelled a heat day. Icing days reach a maximum air temperature of below 0 °C, whereas frosty days have minimum air temperatures below 0 °C.
ii. Precipitation-related events mostly use the height of rain, hail or snow per minute as a threshold for extremes, whereas fog and ice fog use the visibility range.
iii. Wind-related events are divided into the categories of storm, blizzard and tornado. Storms are defined by the Beaufort-scale of wind speeds with the indices 9 (20.8 - 24.5 m/s) to 11 (28.5 - 32.7 m/s) for storm severity. Blizzards are defined by wind speed, air temperature and visibility range. For tornadoes on the other side, the Fujita-scale accounts for the severity.
iv. The last category consists of the so-called combined events, which are a result of different single events. Included in this category are thunderstorms, using the criteria of lightning, heavy precipitation, strong winds and hail. Floods and low water are a result of extreme precipitation. Air and river water temperatures are a result of runoff (precipitation) and air temperatures.

For the different options of electricity supply, namely thermal power plants and renewable energies, a variety of these extreme hydro-meteorological events have an effect, either direct or indirect. Split into the above defined categories, some of these impacts are described in the following.

The availability of cooling water is the most limiting factor for the efficiency of thermal power plants. Therefore, the parameters air temperature, precipitation and combined events have the biggest influence. Basically, two types of cooling water systems are operational. In the once-through cooling system water is withdrawn or removed from a nearby water body, lead through the processing units and discharged back into the water body, either after passing through cooling towers or not. The recirculation cooling water system, on the other hand, uses withdrawn water, re-circulates it several times through the processing units and then discharges back a considerably smaller amount of water than was withdrawn.

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Consequently, a recirculation system shows relatively high water consumption (Feeley III et al. 2008, Strauß 2009). In a changing climate, not necessarily the amount, but the temperature of the water might be the limiting factor, as numerous examples from the United States and Europe already showed in the past that thermal power plants needed to reduce their power output in order to meet legislative thresholds for the maximum temperature of discharged water (US DoE/NETL 2007, Swiss Agency for the Environment, Forests and Landscape (BUWAL) et al. 2004, German Federal Institute of Hydrology BfG 2006). Figure 1 illustrates the connection between cooling systems of thermal power plants, thresholds and a model for the optimal use.

Table 1: Thresholds for extreme weather events according to the German Weather Service (2009) and MetOffice (2009)

Event	*Criteria*
Temperature-related	
Day with icing	Max. air T < 0 °C
Day with frost	Min. air T < 0 °C
Summer day	Max. air T > 25 °C
Heat day	Max. air T > 30 °C
Precipitation-related	
Hail	Precipitation in form of ice; usually diameters of 5-50 mm, rarely to 10 cm
Fog and ice fog	Visibility range < 1 km
Heavy precipitation	>5 mm / 5 min > 7,1 mm / 10 min > 10 mm / 20 min > 17,1 mm / 60 min
Heavy snow	2 cm/h for at least 2 h
Wind-related	
Storm	Beaufort-scale: 9 – 11 9 = storm with 20.8 - <24.5 m/s 10 = heavy storm with 24.5 - <28.5 m/s 11 = gale-force storm with 28.5 - <32.7 m/s
Blizzard	Air T: < -7 °C Wind speed: > 16 m/s Visibility range : < 200 m due to snow fall
Tornado	According to Fujita-scale 6 types/ranges of severity
Combined Events	
Thunderstorm	Lightning Heavy precipitation Extreme precipitation (hail, snow) Strong winds
Floods and low water	100-year event (probability of occurrence)
Water temperatures	Correlation with air temperatures, discharge threshold for thermal power plants 30 °C

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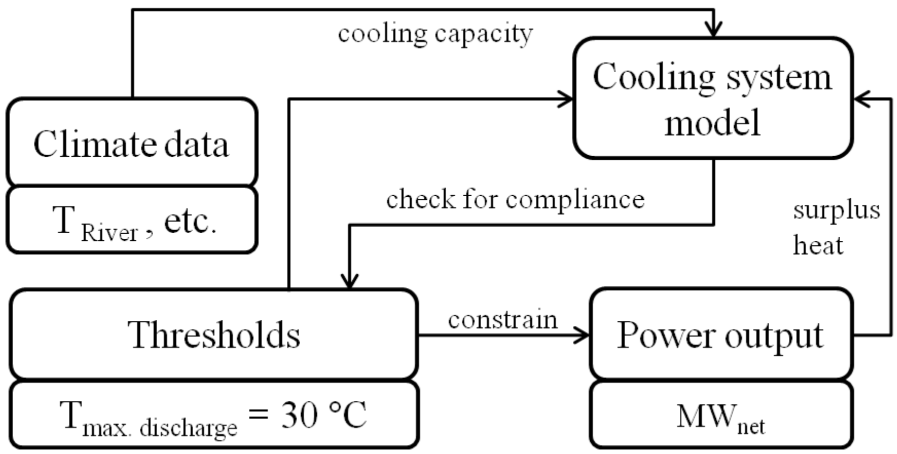

Figure 1: Schematic structure of a cooling system model with the most relevant components (Hoffmann et al. 2010)

Wind-related events often have an impact on the storage and distribution infrastructure and, naturally, on wind power plants. Wind load pressures can cause the following damages among others: the uplift of roofs (O'Connell & Hargreaves 2004, Swiss Re 2005), breaking of power poles due to pressure or due to tree branches falling on the wires (Swiss Re 2005, Heymann 2007), damage to storage tanks in general (Chang & Lin 2006) or specifically by debris impact or denting of metal structures (Bailey & Levitan 2008) as well as bending of pylons, masts and towers.

Lightning strikes into storage tanks often lead to the ignition of flammable tank contents or of leaking oil, sometimes resulting in the blow-off of the tank (Chang & Lin 2006, Stock 2009). Moreover, lightning strikes can damage wind power plants and photovoltaic installations by direct hit or by creeping currents. This may also result in the burn down of the wind power plant (Jonas 2000). More impacts of extreme hydro-meteorological events on power plants and their connected infrastructure are listed in Table 2. This table recapitulates the extreme weather events in the first column with the expected or possible impacts on thermal power plants and renewable energies. A check mark indicates an impact whereas a cross indicates no impact of extreme weather events on the structures of the electricity infrastructure.

3. Adaptation Options for Electricity Infrastructure in the Context of Climate Change

In the following sections, adaptation options structured into cooling facility adaptation, wind impact adaptation and adaptation to thunderstorms and lightning are described.

3.1. Adaptation Options concerning Cooling Water Shortfall

For the adaptation of cooling facilities and options of thermal power plants, the U.S. Department of Energy identified three main categories: the recovery and reuse of water, the use of so-called non-traditional waters, and the use of advanced cooling technologies (U.S. DoE/NETL 2007). The focus will lie on the use of non-traditional waters, for example the use of municipal wastewaters. Representatively, the 3,700 MW nuclear power plant of Palo Verde (Arizona, USA) covers 100 % of its cooling water requirements with treated municipal wastewater of the Phoenix City Sewage Treatment Plant. Stillwell, Hoppock & Webber (2010) state that a wastewater treatment plant requires 0.177 - 0.779 kWh/m³ for purification. A thermal power plant needs 0.1 m³ of fresh water for the generation of 1 kWh. Even though there might be no direct relation between the two types of plants, one can see that the electricity needs of a wastewater treatment plant for one cubic meter of freshwater are about a tenth of the possible generated electricity using one cubic meter of fresh water. Other possible sources of non-traditional waters under research are coal mining and oil drilling waters, as well as coal mine discharge and ash pond effluents. Also, desalinised water can be counted into this category (U.S. DoE/NETL 2007). Additionally, some of the other options are:

- Recover and reuse evaporated water from desulphurisation systems (U.S. DoE/NETL 2007);
- Use hot water from the condenser to dry coal and thereafter use the condensed water (U.S. DoE/NETL 2007);
- Recover evaporated water from the cooling towers (U.S. DoE/NETL 2007);
- Use dry cooling options, like dry cooling towers; and
- Optimise the usage of installed cooling system capacities (Hoffmann et al. 2010).

Whereas the recovery of evaporated water can make up 20 to approx. 40 % of the power plants water requirements, the use of non-traditional waters can meet up to 100 % of the water requirements, as stated in the example above.

3.2. Adaptation Options concerning Wind Impacts

As can be taken from Table 2, wind has an impact on all considered structures. Concerning wind power plants, which are intrinsically vulnerable against wind, the design of the pylon and the friction loss of the cable are important adaptation elements. The tower can be built as a lattice steel pylon, where wind pressure has less surface to attack. Furthermore, the poles must be well anchored into the ground to avoid tipping over or rupture due to wind pressure impact (Bailey & Levitan 2008).

Wind damage of storage tanks or storage areas, especially for coal, can be avoided in several ways. Concrete-sided storage tanks seem more resistant than metal-sided structures, not only against wind pressure, but also against the impact of debris and corrosion (Budnitz 1984). Where metal-sided tanks are necessary, for example regarding the storage of liquids, a concrete coating might be a feasible solution for better protection. Coal stockpiles can be protected by using physical barriers and windbreaks (Cal et al. 1983) or by spraying chemical agents on top of the stockpile to create a wind-resistant crust (Chakraborti 1995). Moreover, regular compaction or grass cover helps to decrease wind-induced losses of coal particles (Hatt 2003).

3.3. Adaptation Options concerning Thunderstorm and Lightning Influences

One of the most obvious adaptation options is the installation of lightning conductors. This simple measure can prevent wind power plants from complete burn down or photovoltaic installations from outage due to direct lightning strike or creeping currents. Like the example of wind impacts, the construction of concrete-sided storage tanks better protects the contents from lightning impact than metal-sided tanks do (Budnitz 1984). Also, where metal tanks cannot be avoided, a concrete coating can help protect the contents.

Since thunderstorms often imply high wind speeds extreme precipitation, hail and lightning, the adaptation of wind power plants is important. Especially the tips of the blades are vulnerable against impacts of hail stones which can erode the material (Jonas 2000). Moreover, frost and ice accretion can enforce this effect. Therefore, heating wires to prevent ice accretion can be installed at the rims of the blade.

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Table 2: Identification of the impacts of extreme events on power plants. A check mark (✓) indicates an impact, whereas a cross (X) indicates no impact of the extreme event defined in the first column on the power plant installation in the following columns.

Event	*Coal-fired power plant*	*Gas power plant*	*Oil power plant*	*Hydropower plant*	*Wind power plant*	*Photovol -taics*
Temperature-related						
Heat	✓	✓	✓	✓	✓	✓
Cold/Frost	✓	✓	✓	✓	✓	✓
Precipitation-related						
Hail	✓	✓	✓	X	✓	✓
(Ice) Fog	X	X	X	X	X	✓
Heavy precipitation	✓	✓	✓	✓	X	✓
Heavy snow	✓	✓	✓	✓	✓	✓
Wind-related						
Storm	✓	✓	✓	X	✓	✓
Blizzard	✓	✓	✓	X	✓	✓
Tornado	✓	✓	✓	✓	✓	✓
Combined events						
Thunderstorm	✓	✓	✓	X	✓	✓
Floods or low water	✓	✓	✓	✓	X	X
Water temperatures	✓	✓	✓	X	X	X

4. Planning Process and Decision-Support for Power Plant Operators

In the face of a changing climate, most power plant operators need decision-support to choose valuable adaptation options for their specific site. The first step of such a decision-support is always the identification of the problem, and afterwards a well-structured process of the cyclic procedure of plan, do, check and act as recommended by the Federal Ministry of the Interior in Germany (BMI 2008). This leads to a scientifically based implementation of adaptation measures. The results presented in this section are taken from an industrial research project and are site-specific. The two approaches presented here are to be conducted in parallel and not separately.

4.1. Identification of the Problem and Concept Establishment

First of all, Table 3 helps to identify the general impacts of hydro-meteorological events at a power plant site. Afterwards, site-related operation manuals, standards and emergency plans need to be examined concerning gaps, vagueness and needs for more or better protection and adaptation. Usually, official channels, like the meteorological services, provide maps and data for the energy suppliers in order to assist early warning. But, those maps often have a low spatial resolution concerning the power plant site and the application of those maps for planning issues is limited. In addition, Table 3 shows some of the direct and indirect impacts that power plant structures may suffer from severe weather with a focus on flooding.

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Table 3: Direct and indirect impacts of extreme hydro-meteorological events on power plant structures and equipment, focus lies on flood events (Sieber née Schulz 2011a).

Structure	*Direct Influence*	*Indirect Influence*
Buildings (offices, recreation)	Intrusion of water Damages to substance Damages to interior	Contamination due to mud as well as hazardous substances
Access roads	Overflowing	No access to electricity infrastructure Difficulties for evacuation
Cooling facilities	Flooding/filling of cooling tower pond to avoid floating[2] Shortfall in water supply	Contamination due to hazardous substances
Boiler/reactor	Intrusion of water	Contamination due to mud as well as hazardous substances Shutdown due to lack of cooling water
Storage rooms/tanks/areas	Intrusion of water Burn down due to high temperatures Bending Wind-blown dispersal Ignition due to lightning impact	Wetting of hazardous substances due to wrong storage Creeping currents lead to ignition
Security places	Intrusion of water	Contamination due to mud as well as hazardous substances
Masts/towers/pylons	Bending, breaking Ignition due to lightning impact	Shutdown of wind power plants due to high wind speeds
Cables/wires	Sagging due to high temperatures and ice accretion	Branches can cause rupture when they fall on the wires

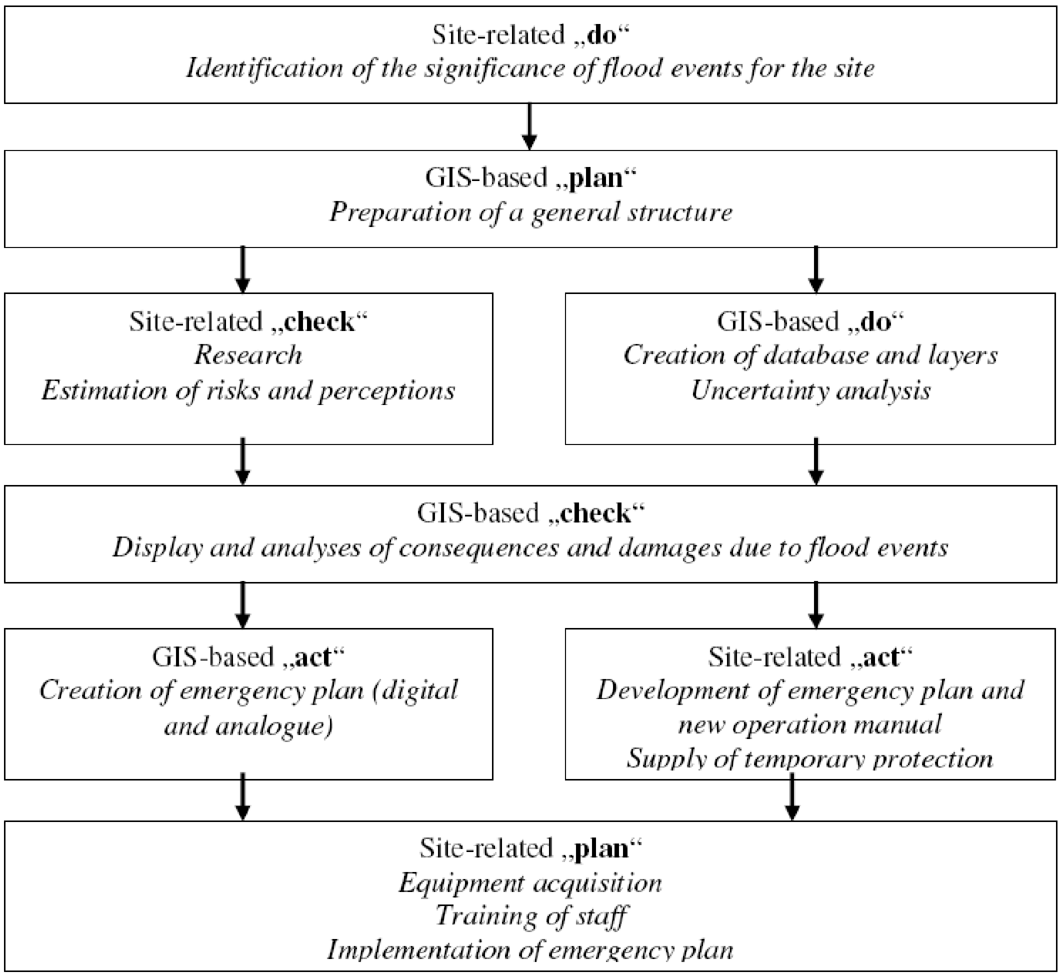
4.2. Site- and GIS-related Approach for Decision-Support

In Figure 2, the process of the plan-do-check-and-act procedure is shown. This cyclic approach allows power plant operators to prepare the power plant site step by step for adaptation. The process is separated into the site-related and the GIS-based approaches which run in parallel in order to create an integrated measure planning. The site-related approach aims at a continuous improvement of preventive measures. It starts with “Do”, the identification of the problem itself as described in the chapter above. Afterwards, gaps in the protection of the site are identified and lead to the comparison and estimation of risks (“Check”). The third step encompasses “Act”; the development of a feasible emergency management plan and the acquisition of temporary protection measures in case of emergency. The last step “Plan” contains the training of staff and implementation of the planning approaches on-site. The GIS-based approach, on the other hand, starts with “Plan”. A general structure of the management process, data requests and background research are comprised in this step. Afterwards, the data are included and handled in the geographical information system, which is the step “Do”. The third step “Check” contains the analyses of

[2] The term “floating” described an uplift of the cooling tower pond due to upward pressing groundwater. To avoid such floating, the cooling tower pond is filled with water in advance of a flood event.

data and the preparation of scenarios with adaptation options in the future. The consequences of this step are, for example the prevention of damages and the maintenance of the operating processes. The last step is the provision with easily understandable and easily accessible maps and plans in order to avoid wrong measure planning in case of emergency of the power plant operator ("Act").

Figure 2: Overview on steps taken within the circle of plan-do-check-and-act concerning site-related and GIS-based approaches (Schulz (Sieber née Schulz) 2011b).



5. Summary and Conclusions

The main conclusion that can be drawn from this paper is that extreme hydro-meteorological events have several impacts on the electricity infrastructure. Some of these impacts have already been identified at the early stages of power plant operation. Since the 1980s "adaptation" options are described. At that time, adaptation was not a matter of climate change, but of extreme events. Those seem to have statistically increased in frequency and intensity due to climate change in the last years. Therefore, this topic gains more and more notice and interest by energy suppliers and the public.

The need for adaptation is clear. Thermal power plants are subject to reduced water availability either in quality or quantity. Therefore, especially cooling facilities potentially need a retrofit and modification in operation and design. Also, wind, extreme precipitation and lightning have impacts on structures as the examples of wind power plants, photovoltaic installations and storage structures showed. Those negative effects should be reduced by implementing adaptation options into everyday use and planning of electricity generation and distribution.

The site-related and GIS-based risk-management approaches are currently implemented at a test site, therefore no specific data can be included in this paper. Nevertheless, the advantages of such an integrated approach are clear. The extensive possibilities of data storage and processing in a GIS create an added value compared to the usual planning procedures since local and process data can be joined and analysed. The approach presented here is part of a comprehensive concept including the described events impacting the electricity infrastructure as well as the possible adaptation measures for a robust supply of electricity.

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