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LETTER

US power plant sites at risk of future sea-level rise

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Abstract

Unmitigated greenhouse gas emissions may increase global mean sea-level by about 1 meter during this century. Such elevation of the mean sea-level enhances the risk of flooding of coastal areas. We compute the power capacity that is currently out-of-reach of a 100-year coastal flooding but will be exposed to such a flood by the end of the century for different US states, if no adaptation measures are taken. The additional exposed capacity varies strongly among states. For Delaware it is 80% of the mean generated power load. For New York this number is 63% and for Florida 43%. The capacity that needs additional protection compared to today increases by more than 250% for Texas, 90% for Florida and 70% for New York. Current development in power plant building points towards a reduced future exposure to sea-level rise: proposed and planned power plants are less exposed than those which are currently operating. However, power plants that have been retired or canceled were less exposed than those operating at present. If sea-level rise is properly accounted for in future planning, an adaptation to sea-level rise may be costly but possible.

1. Introduction

The electric power system is one critical infrastructure system that ensures the functionality of society and its operations depend crucially on the reliability and functioning of power plants. Many power plants are located near the coast. Unmitigated greenhouse gas emissions may increase global mean sea-level by up to 1 meter within this century (IPCC 2013). This corresponds to the upper limit of the likely range for sea-level rise under the so-called representative concentration pathway (RPC) that lead to a total radiative forcing of 8.5 W m^{-2} by the end of this century (Moss *et al* 2010, Meinshausen *et al* 2011). This greenhouse gas concentration is expected to occur without effective mitigation policies and is therefore often considered as the business-as-usual scenario. Contributions to sea-level rise caused by global warming include thermal expansion of oceans, melting of glaciers and ice caps on Greenland and Antarctica (IPCC 2013).

Such elevation of the mean sea-level enhances the risk of flooding of coastal areas without additional protection measures (Hanson *et al* 2010, Hinkel *et al* 2014, Aerts *et al* 2014, Maloney and Preston 2014). In this study we assume that the occurrence probabilities for storms, which cause surges, are not changing with global warming. However, hurricanes, which cause storms at the US East and Gulf Coast, are expected to become more frequent and intense under global warming (Lin *et al* 2012, Mendelsohn *et al* 2012, Little *et al* 2015). Moreover, we neglected changes in coastal geomorphological dynamics (Passari *et al* 2015) and tidal constituents (Arns *et al* 2014) that also contribute to future extreme water levels. Additionally, coastal zones agglomerate industrial and commercial facilities. These are connected via vital infrastructure systems, such as the electrical grid and the connected generation facilities.

Many power plants are located near shorelines to draw seawater for cooling purposes. Present protection measures might not be sufficient for future sea-level extremes during, for example, storm surges. Failed power generation might be substituted by unused power capacities from any location within the energy distribution grid. However, substituted energy generated by peak load power plants is more costly than those from base load power plants.

In this study we determine those locations of power plants in the US that are now safe to 100-year floods, but come into reach of such events at the end of this century. We included power plants of all energy sources that are currently operating or are in the planning process.

2. Methods of computation

2.1. Extreme sea-level distributions and sea-level rise

The National Oceanic and Atmospheric Administration in the US provides extreme sea-level distributions for 81 long-term tide gauge stations along the US Coast (Zervas 2013). Extreme sea-level distributions provide the probability of a certain water level above mean higher high tide and can be expressed as general extreme value distributions. The shape parameter determines if a distribution takes the form of a Weibull, Gumbel or Frechét distribution (Kotz and Nadarajah 2000). In order to obtain the exceedance probability per year for a given sea-level value above mean higher high tide we integrated the distribution above this sea-level value.

Upon these distributions we added the upper limit of sea-level rise, which is expected to be 1 meter by the end of this century (IPCC 2013). Contributions to this sea-level rise include the thermal expansion of the oceans, melting of glaciers and melting of ice-caps on Antarctica and Greenland.

In other words, we assumed that distributions are shifted to more extreme sea-levels by sea-level rise but their shape remains unchanged. Hence, neglecting changes in hurricane activity, coastal geomorphological dynamics and tidal constituents that also contribute to future extreme water levels.

2.2. US power plants

The US Energy and Information Administration provides geographic locations of all closed, operational, planned and proposed US power plant sites (EIA 2013). Their corresponding elevations relative to the North American Vertical Datum of 1988 (NAVD88) are obtained from the National Elevation Map of the US Geological Survey (Gesch 2007, Gesch *et al* 2002). The National Oceanic and Atmospheric Administration provide gauge datum data that we used to compute elevations above mean higher high tide. Firstly, we adjusted for the deviation of NAVD88 to mean sea level. Secondly, we subtracted the mean higher high tide of the nearest tide gauge station of a power plant site from its elevation above mean sea level.

For each power plant site we allocated an extreme sea-level distribution that corresponds to the nearest long-term tide gauge station. There are data available from 81 tide gauge stations in the contiguous US that have a long-term data record.

2.3. Additional exposure to 100-year sea-level extremes

In our analysis we considered power plants of all energy sources within 10 km of the coastline in the contiguous US. We included operating, planned and proposed power plants of all energy sources. A power plant site is considered exposed if an extreme water-level, i.e. the water level above mean higher high tide, reaches its present tidal-adjusted elevation. In order to obtain the exposure at the end of this century we shifted the extreme water-level distribution by 1 meter of sea-level rise.

The integral over the distribution above the tidal-corrected elevation delivers the exceedance probability. A power plant is exposed to 100-year events if its elevation is exceeded by extreme water levels with an exceedance probability of more than 1%. In other words, a power plant with an elevation that is below an extreme water level with an exceedance probability of more than 1% is exposed to 100-year events. We intend to determine those power plants that are today out-of-reach of 100-year floods, but will be pressured by those under a sea-level rise of 1 meter. Therefore we considered all power plants that have exceedance probabilities of more than 1% in 2100 but less than 1% today. We considered the upper 95 percentile of the extreme sea-level distribution to give an upper estimate for the 2100 exposure. This study ignores the presence of protection measures, such as levees. The presence of protection measures would only effect the results if they represent sufficient protection for 100-year flood events.

3. Results

We determined power plant sites that are now safe to 100-year extreme sea-level but will be at risk within this century due to global warming (figure 1). Circle sizes in figure 1 scale with the exposed plant's power capacity. Power plant sites that will be additionally at risk to climate change induced sea-level rise this century cumulate a total of 25 GW of operating or proposed power capacities. We define the exposure of individual or aggregated power plant site as their capacities that will be additionally at risk to 100-year events by the end of this century.

Exposure per state varies by over five orders of magnitude and is indicated by color in figure 1. Aggregated exposure ranges from 9 MW in Georgia to 11 GW in Florida. At the West Coast the largest exposure is shown by California with 315 MW. At the East and Gulf Coast exposures sum up to several GW. In this area hurricanes occur and contribute to

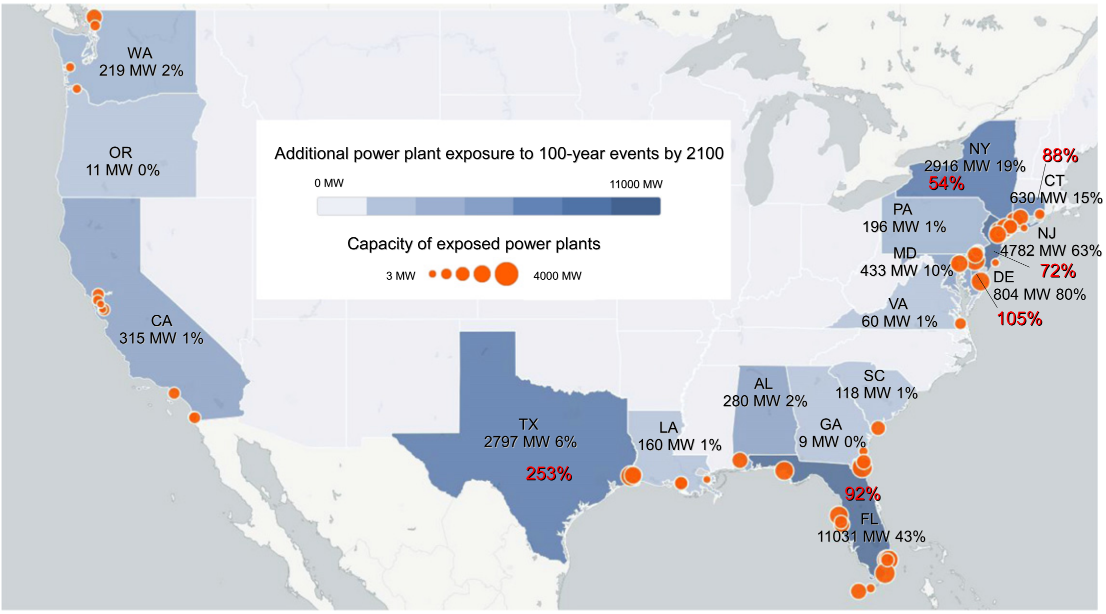

Figure 1. Additionally exposed US power plant sites under unmitigated sea-level rise to 100-year extreme sea-level. Colors represent the additional power capacity that will be at risk of a 100-year flood event compared to present-day. Red percentages give this number in relation to currently exposed capacities with respect to 100-year events. Black percentages give this number in relation to the mean power generation, i.e. the average power load, of the state.

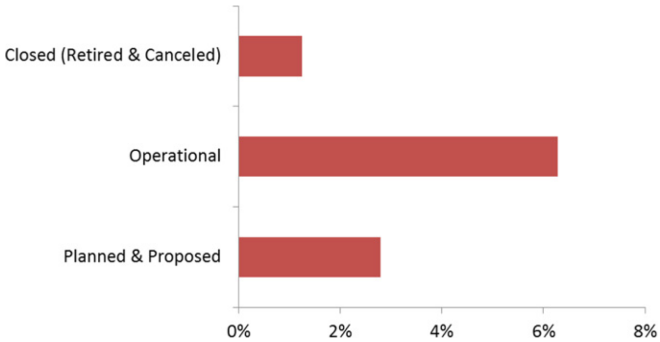

Figure 2. Additionally exposed US power capacity to 100-year events in 2100 as fraction of the present-day total for closed, operating and proposed power plants. Proposed and planned power plants are less exposed than those which are currently operating. However, power plants that have been closed, i.e. retired or canceled, were less exposed than those operating at present.

storm surges. The largest exposure per state in the hurricane region with 11 GW is found in Florida. Power capacities of 2.8 GW are exposed in Texas and at the East Coast New Jersey and New York show the largest exposures with 2.9 GW and 4.8 GW, respectively.

The ratio of exposed power capacities per state relative to the present amount of exposed power capacities to 100 year events is denoted in red percentages in figure 1. Ratios are given for exposure accruals per state above 600 MW.

The share of future additional exposure per state relative to its average present energy generation, which represents the average energy production, is indicated by black percentages in figure 1. However, available power capacities are larger than the average load in order to add power generation at peak times if necessary. Additionally exposed power capacities relative to today's average generation capacities are largest in Delaware, New Jersey and Florida. This share mounts up to 80%, 63% and 43%, respectively. In contrast, the relatively large amount of 2.8 GW absolute additional exposure in Texas represents only 6% of Texas' total average power generation.

We compare the additional exposure of power plant sites of closed, currently operating and proposed power plants in figure 2. While the projected additional exposure among operating power plants represents 6% of the total operating capacity in the contiguous US, it reduces to 3% for proposed power plant capacity. However, power plants that have been closed, i.e. retired or canceled, were 1.5% less exposed than those operating at present.

4. Discussion and conclusion

Our analysis projects the present-day power plant structure, including operating and proposed power plants, to the end of this century, where sea-level may rise by up to 1 meter. Note that we did not intend to model the amount and structure of future power plant sites. However, power plant sites in the vicinity of shorelines will be stressed by future sea-level extremes. These conditions require either enhanced protection pressure or relocations of power generation and therefore may represent a driver for structural change in the energy sector. Relocation seems easiest for power generation that is independent of cooling sea-water. The additional amount of proposed or planned power plant sites at risk is less than currently operating power plant sites (figure 2). This may be due to the increase of renewable energy sources among proposed power plants, which are independent of coastal cooling water.

One might argue that as long coastal economic centers are provided with comprehensive protection measures, coastal power plants are secured as well. However, since sea-water cooled plants are located at the foremost flood frontier while they serve as a key-infrastructure for areas further inland. The enhancement of cities' resilience should improve the capability of urban areas to cope with temporary flooding without failing power capacities.

Challenges arise predominantly for coastal power plants that depend on sea-water cooling. Since it is expected that also river floods will intensify with global warming (IPCC 2012) relocations to river sites does not necessarily diminish the protection pressure. Furthermore, the potential for flooding in low-lying coastal areas increases with changes in the joint distributions of storm surge and heavy precipitation (Wahl *et al* 2015). There are a range of measures available from levees around the power plant to large scale sea walls for entire bays. However, the latter solution might not be sufficient under future river floods for bays with estuaries. The question arises if an energy structure with a base load power generation that depends on sea-water cooling and river water cooling is resilient to future flood conditions. That is especially relevant because studies published after the IPCC (2013) report suggest that sea-level rise by the end of the 21st century may be higher (Levermann *et al* 2013, Joughin, Smith, and Medley 2014, Favier *et al* 2014, Rignot *et al* 2014, Levermann *et al* 2014, Feldmann and Levermann 2015) and sea-level will continue to rise beyond the 21st century (Solomon *et al* 2009, Eby *et al* 2009, Levermann *et al* 2013, Dutton *et al* 2015).

In this study we ignored the presence of any protection measures, such as levees. The presence of protection measures would affect the results if they represent sufficient protection for 100-year flood events. However, the existence of present day protection measures does not guarantee their existence at the end of this century. Our analysis merely determines the amount of additional power production capacity that will be at risk within this century for events with larger return periods than 100 years. Therefore, we estimate the future protection pressure for power plant sites that needs to be considered. An adherence to coastal power plant sites requires an examination of the present-day protection and possible enhancements.

We did not implement postglacial rebound effects, which occur predominantly at coastal areas near the Canadian border and are orders of magnitude smaller than the applied sea-level rise. Furthermore, extreme sea-level distributions above mean higher high tide at each power plant site correspond to the nearest one of one out of 81 long term tide gauges provided by the National Oceanic and Atmospheric Administration (Zervas 2013). However, extreme sea-level distributions may vary strongly due to coastal shape and submarine ground. Nevertheless, future storm surge risk may exceed our estimated impacts at the East and Gulf Coast if one includes intensifying hurricane activities in the Atlantic Ocean (Lin *et al* 2012, Mendelsohn *et al* 2012) and changes in the Atlantic overturning circulation (Levermann *et al* 2005, Landerer, Jungclaus, and Marotzke 2007, Yin 2015) in the analysis.

In summary, the protection of coastal power plants is a significant challenge that needs to be accounted for in estimates of the safety and costs in future planning.

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