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Abstract

Cold and heat waves represent a significant problem for the electricity generation sector. The disruptions cold and heat waves can cause in power production are beyond their consumption impacts through, for instance, higher peak demand. Unexpected stops at thermal or nuclear power plants by excessively high-temperature water constitute clear examples of this. In this invited paper, we use past case studies to analyze the impact of these kinds of events on power production. Subsequently we discuss how events of this nature may evolve over the future in view of their association to climate change. Although the review is not exhaustive, we do expose some ideas that may be relevant for decision making in this area.

Keywords: extreme temperatures; heat waves; cold waves; energy; power

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1. Introduction

Extreme weather represents a very significant problem for all activities that rely on average and predictable weather patterns. This problem is transversal throughout natural systems and life. Extreme weather events are related to the extreme values of environmental variables. One of these variables is temperature and, when such extreme values persist across several days, a cold or heat wave takes place for low and high values of temperature, respectively. However, a proper definition of such events is missing. Given the increasing societal concern about these episodes over the last years, the World Meteorological Organization (WMO) established a task team in 2010 to provide a proper definition. The most recent published report [1] proposes the following definition for a heat wave:

"A marked unusual hot weather (Max, Min and daily average) over a region persisting at least two consecutive days during the hot period of the year based on local climatological conditions, with termal conditions recorded above given thresholds".

And, in a similar way, it defines a cold wave as:

"A marked and unusual cold weather characterized by a sharp and significant drop of air temperaturas near the surface (Max, Min and daily average) over a large area and persisting below certain thresholds for at least two consecutive days during the cold season".

The proposed definition recognizes the regional features of what may be considered an extreme event. That is, while a value of temperature may be considered extreme for a given region, it may be completely normal for another.

The relevance of this matter is reinforced by the fact that climate change also affects extreme weather. Indeed the impact of climate change has regularly been attributed to such events over the last years (see, for example, the reports by the American Meteorological Society since 2011; e.g. [2], https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorologicalsociety-bams/explaining-extreme-events-from-a-climate-perspective/). Also the last report by the Intergovernmental Panel on Climate Change (IPCC) states that anthropogenic climate change is likely to have more than doubled the probability of heat wave ocurrence in some regions of the planet [3]. Climate simulations project that by the end of the current century these heat waves will be "more intense, more frequent and last longer".

One of the activities seriously endangered by extreme weather (and heat and cold waves in particular) is energy production and consumption. A report in 2014 by ClimateCentral points out that blackouts due to extreme weather have multiplied by ten in the US between the 1980s and 2012 and many of them have resulted from cold and heat waves [4]. The energy sector is involved in this problem in two different ways: as well as being affected, it has also been a major cause of it since the early 20th cenury as a significant greenhouse gas (GHG) emitter due to power generation through fossil fuels. Yet it is also greatly affected by extreme weather, which introduces a level of unpredictability for power generation and consumption that affects operations, price volatility and at the end may as well have impacts on energy security. For example, a heat wave can make it impossible to generate electricity in a nuclear plant yet at the same time it may increase energy demand because of air conditioning.

The literature presents many examples of how extreme weather can put the power grid and the electricity generation system under stress and finally lead to blackouts. Moreover the side effects of increasing energy consumption during heat and cold waves are known to include increased levels of tropospheric ozone in urban environments. This is associated to health problems and to a positive feedback of the urban heat island effect and thus extra energy consumption [5,6].

In particular, extreme weather phenomena affect energy production and its facilities. They cause supply cuts of different magnitudes and affect other infrastructures depending on the energy supply [7]. An evident example is the Northeast blackout of 1965 linked to a heavy power demand and cold weather in a very relevant US region. Looking again at some figures for the US, we observe that the estimated average annual cost of power outages caused by severe weather events (including hot and cold waves, as well as hurricanes, floods, etc.) ranged between US$ 18 and 33 billion between 2003 and 2012 [8].

Recent efforts acknowledge the relevance of this issue [9,10]. Some examples are the European Climate Energy Mixes (ECEM), Weather Intelligence for Renewable Energies (WIRE), or Clim4Energy in the framework of the Copernicus Climate Change Services (http://climate.copernicus.eu). All of them intend to provide better information and tools for decision makers working in the interface between weather, climate and energy. However it is worth noting that the last IPCC report on the impact of climate change on renewable energy resources (now six years old) makes no specific statements concerning cold waves or heat waves [11].

Therefore, this paper focuses on how heat and cold waves can introduce a significant stress on the electricity generation sector and on how climate change has affected them and is likely to impact them over the next decades (with a discussion of the role of intra and interannual weather forecast). The article is also interested in identifying the factors that may increase the resilence of the electricity generation sector through adaptation. With that purpose it examines and discusses heat and cold waves separately by reviewing some case studies. The reason for such a separate analysis is the diversity of effects associated to extreme events: heat waves affect the generation, transmission and distribution of electricity and may lead to blackouts or reductions in the electricity supply [12]. However, cold waves are more likely to affect the energy network and provoke electricity supply cuts [13].

2. Heat waves

During heat waves high temperatures affect the generation capacity of fossil fuel and nuclear powered plants, as well to renewable technologies, due to increased air and water temperature. In the case of nuclear power plants, an increase of 1 ºC reduces the energy supply by about 0.5% via its effect on thermal efficiency. For its part, every 5 ºC increase in water temperature represents a 1% loss of efficiency [14]. During droughts and heat waves, the loss of electricity production may therefore exceed 2% per degree Celsius [15]. In this context, factors such as temperature limits for discharging water could represent a loss of between 12% and 16% of the generation capacity of central and eastern US power plants by the middle of this century [16]. Also heatwaves could lead to electricity supply deficits of up to 19% in California by the end of the 21st century [17]. In addition, operating costs may increase during heat waves given the need for more staff (requiring an increase of between 50% and 100%) and a bigger stock (an increase of between 10% and 20%), and cascading failures leading to blackouts will become more likely [18].

Conversely, transmission and distribution systems lose efficiency at high temperatures because they limit the power of the transformers and lines and expand the resistance of electric transmission in networks, thereby increasing energy losses. The capacity of transformers decreases by 1% for each degree Celsius; in copper lines the temperature of the resistance increases by 0.4% for each degree Celsius. Hence, total network losses increase 1% for every 3 ºC [12]. Moreover, heat waves increase cooling demands, thereby boosting electricity consumption to its highest value and testing the ability of the system to meet this demand. In this sense, demand could increase by as much as 21% on particularly hot days by the end of the century [16].

We next provide some examples, based on the existing literature, of the impact of heat waves on the energy sector. During the 2003 heat wave in France, rivers reached record temperatures and caused a slowdown in the cooling process of nuclear plants. This reduced power generation capacity by 4,000 MWh and nuclear power generation by 5.3 TWh, even though the actual electricity supply was unrestricted. For the same heat wave in Spain the cumulative electricity demand in August peaked nearly to 13% above the values for the previous year [19]. During the California 2006 heat wave, transformers warmed to the extent of breaking the fuses and burning the insulation; this resulted in short circuits causing electricity outages that affected over 80,000 people throughout several days and cuts that affected around 1.3 million clients [12,20]. Also in 2013, a report by the US Department of Energy [20] already listed up to twelve crises affecting different energy production infrastructures in the US since 2006 due to extremely high temperatures, including nuclear plant shutdowns due to heat waves.

In 2007 the State of Victoria (Australia) suffered a power outage resulting from a heat wave that also caused fires. As a result, about 690,000 electricity consumers suffered power outages. This included about 70,000 businesses, which were at a standstill for over a week in some cases. Unsupplied electricity amounted to 7,100 MWh, with a direct cost of AU$ 235 million. This together with indirect impacts (interruptions in transport, communications, health, etc.) entailed an economic cost of about AU$ 500 million. For large firms, direct costs ranged between AU$ 0.05 and 30 million per affected site [21]. In March 2008 the nearby South Australian region also suffered heat waves leading to record electricity demands on three separate occasions. This caused problems to maintain the electricity supply on the transmission grid; it reduced the instantaneous reserve margin up to 7%, and it ultimately led to rocketing electricity market prices. Thus, the price exceeded AU$ 5,000/MWh 26 times, and it exceeded AU$ 7,000/MWh six times with an average price of AU$ 353/MWh in March. The cumulative total price increased by over AU$ 150,000 and forced the electricity market operator to set a price cap. The heat wave was claimed to have allowed electricity companies to obtain extra revenues of nearly AU$ 200 million [22]. The heat wave suffered by Southeast Australia in the summer of 2009 caused financial losses estimated at AU$ 800 million, mainly resulting from power outages, interruptions in transport service and response costs [23]. The electricity sector was the most vulnerable to heat, which particularly affected the transmission and distribution systems, on the verge of collapsing given that they were operating at close to full capacity. Interruptions occurring in major transportation lines caused blackouts that left hundreds of thousands of homes and businesses without electricity on 30 January and accounted for AU$ 100 million in damages [24].

3. Cold waves

The effects of cold waves on the energy sector include breakdowns in power plants and reduced oil and gas production [25]. They could also cause failures in airlines and towers, since ice and snow may accumulate in the insulation under freezing conditions, bridge them and cause a flashover [26]. Again, we next provide a quantification of impacts based on the evidence from existing case studies.

During the cold wave suffered in Canada and the United States in 1998, over 4 million people were left without electricity and heating. The cold wave also destroyed 120,000 km of power lines and communications. This included 130 major transport towers valued at US$ 100,000 each and 30,000 posts costing US$ 3,000 each. Under these circumstances, the total economic cost (not just for the electricity sector) amounted to C$ 1.5 billion in Canada and US$ 1 billion in the United States [25]. Similarly, the cold spell affecting Texas, Arizona and New Mexico in the US during February 2011 led to several blackouts and natural gas shutdowns [27].

However, cold waves can also cause significant energy demand increases. The cold wave affecting the United States in the winter of 1976-77 represented a US$ 3,800 million increase in costs associated with energy consumption that included higher electricity, heating and coal costs [28]. A cold wave in France in January 2010 also resulted in a peak in demand for natural gas; every degree Celsius reduction in winter temperatures represented an increase of about 100 GWh in daily natural gas consumption [29]. Also as recently as January 2017 Spain faced a rush in the prices of electricity because of the combination of a cold wave [30] and other market constraints such as the need to supply electricity to France because of several stops for nuclear plant maintenance and an increasing price of fossil fuels. Electricity prices peaked on 25 January 2017 with a mean price of 112.8 Euro/MWh, the highest ever recorded in Spain (http://www.esios.ree.es/es/mercados-y-precios).

Another problem associated with extremely cold temperatures representing a substantial threat for the energy sector is freezing rain. This is liquid, supercooled precipitation that freezes when coming into contact with solid objects, forming a coating of ice [31]. Freezing rain represents a threat for the power transmission lines as it could lead them to fail. Several examples are listed in the literature and they include blackouts affecting up to 80% of the population in some countries, and more than 200 km of power lines and major cities such as Moscow [32]. Again, climate change may have an impact on this meteorological phenomenon: it has been found that for eastern Canada the intraannual distribution of freezing rain events will change as they will be more frequent from December-February and less frequent in other months by the end of this century [33]. However, climate change will likely lead to a reduction in the number of such events in the eastern coast of North America [34].

4. The role of seasonal forecast

First of all it must be clear that huge differences exist in the use of weather/climate information for long-term planning and for daily operational response for power production. In this section we focus on the role of seasonal forecast without going into these differences in depth.

It is clear that when discussing the relationship between weather and energy production, one cannot overlook the role of seasonal forecast. This is because energy production and demand patterns are very different for each season. Also energy prices are sometimes decided on a seasonal basis. Therefore, having climate information on a seasonal level is usually considered of the outmost importance by the power sector, investment funds, reinsurance companies, etc. Moreover seasonal and intraseasonal weather forecasts have progressed considerably during the last decade, making it now possible to provide probabilistic assessments of energy production and consumption [35–37]. The skill and potential of seasonal forecasting for the energy sector depends mostly on how realiable the forecast is for a region. In Europe, for example, where the North Atlantic oscillation (a very well studied climatological pattern [38]) fingerprints winter weather, the last results of seasonal forecasts considering it show promising and useful oucomes for the energy sector [39], even allowing for results up to one year in advance [40].

Moreover, seasonal forecasts combined with weather typing can be a powerful tool for evaluating the recurrence of episodes that may put the energy balance under stress. This may also prove useful to plan how to work around potential problems [41]. Yet it must be stressed that this involves using meteorological and climate models with a well resolved stratosphere (at least for winter) [42], which is something uncommon as of yet. An example of its application is the possibility of getting seasonal forecasts for water temperature (that depend on flow and air temperature) in the Rhine River linked with the NAO [43]. Such forecasts have also proved to detect potentially cold winters, such as the winter of 2005-2006 in the United Kingdom, which had a huge impact on energy prices [44]. Moreover, although summer seasonal predictability is known to be more dificult, improved models have been developed during the last years that are now able to forecast heat waves like the one affecting France and Italy in July 2015 [45], which led to several blackouts.

Other climatic phenomena related to seasonal forecast with potential for significant improvements on predictions for the energy sector are the variations of the stratospheric polar vortex and stratospheric sudden warmings. Yet this again implies the use of models with a well resolved stratosphere such as HadGEM-GloSea5 or WACCM [42,46,47]. The proven existence of a link between atmospheric blocking and heat waves and cold waves with impacts on the energy sector may be forecasted using seasonal and subseasonal scales [48–51].

4. Discussion

Herein we have briefly reviewed how heat, cold waves and generally extreme temperatures represent a risk for the energy sector. We also discussed some clues on how climatic variability relates to seasonal predictability. From the preceding it is possible to extract some conclusions that support a number of recommendations:

- Return periods of extreme temperatures (and other extreme weather events) change with climate change. Such variations may lead to lack of accuracy concerning future physical efficiency and economic viability during the planning of new power production infrastructures. Therefore, the decision process for setting up these facilities should include a complete assessment of potential changes in such return periods.
- Single extreme weather events are less likely to pose a risk for the power production sector and energy security than are compound extreme events. Compound events are defined as "(i) two or more extreme events occurring simultaneously or successively, (ii) combinations of extreme events with underlying conditions that amplify the impact of the events, or (iii) combinations of events that are not themselves extreme but lead to an extreme event or impact when combined" [1]. That is, a cold spell itself could represent a problem but, if enough water is stored in reservoirs, hydropower production can address the problem. However a cold wave combined with a prolonged drought period, or more physically-extreme low accumulated precipitation over a long period of time can represent a clear threat for energy security. This is specially relevant if we take into account that water scarcity and other alterations of the hydrological cycle are well-known consequences of climate change. We therefore suggest that an increasing effort should be set forth both from the point of view of climate sciences and economics to

address the issues concerning the probable incidence of compounded extreme weather events and their impact on the energy market.

- Where they do not exist yet, vulnerability assessments and resilence plans for the energy sector should be developed both at the government and company levels. An example of this is a recent report by the U.S. Department of Energy [52]. In this sense, the report identifies a compound event of a drought and a heat wave that affected a power station in Braidwood (US) in 2012.
- The existence of potentially huge benefits from improvements in seasonal forecasts and their application in the energy sector, make it likely for bigger investments in this field to generate sizeable returns. This should include better studies of El Niño-La Niña seasons. In some way, most of the regions of the planet have overlooked this link to date despite their well-known global-regional teleconnections and the fact that they introduce interannual variability that can heavily affect energy production and demand.
- Making a pre-emptive investment to construct or renovate plant cooling towers could avoid the loss of power generation associated to heat waves. However, the cost of renewing existing cooling towers in a plant to allow for 2-3 ºC cooler water would be approximately 2.5 Euros/kW, while the cost for building the towers would amount to 80 Euros/kW. For its part, avoiding increased losses in the transport network would require an investment of 40 Euros/kW. In this context, the actual annual regional costs for adapting to climate change in 2080 would, in function of the European region, range between 166 and 527 million Euros due to increased air temperature, and between 67 and 308 million euros due to a greater recurrence of heat waves [14].
- In the near future decision making systems for energy production should incorporate potential effects of extreme events on a daily basis. This must be done by automatically including meteorological information from observations and models and decision algorithms. Some tests using such methodologies have already been performed successfully [53]. Integrating Big Data in the decision process may also improve the management of potential crisis from heat and cold waves [54].

In sum, as is the case of most agents and sectors, energy production must also adapt to attain higher levels of resilence given the threat of climate change and extreme weather, and there seems to be great room for improvement. For example, a study by the World Bank in 2011 failed to find adequate adaptation measures in major energy sector programs or projects despite having experienced real problems during the 2003 and 2006 heat waves in Europe and the US [55]. This comes to show that more and larger efforts are clearly required.

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