Assessing the Impacts of Extreme Temperatures and Water Availability on the Resilience of the GB Power System

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***Abstract*—Extreme weather events or more in general changing environmental conditions (for instance due to climate change) might have significant impacts on future power systems, threatening their resilient operation. In this context, this paper provides a quantitative analysis of the temperature and water availability effects on power system resilience. Differently from most existing work that only addresses the impact on individual power plants and independently of the context, a system level assessment is conducted here through a time-series model that specifically considers the temperature sensitivity and the impact of water availability on the cooling systems of all conventional thermal power plants, as well as the temperature sensitivity of line capacities and of electrical demand throughout the network. Sequential Monte Carlo Simulation (SMCS) is used to capture the stochastic impacts of such phenomena and derive relevant impact metrics. The model is demonstrated on a 29-bus reduced representation of the Great Britain (GB) transmission network. Several future scenarios for future generation and demand are formulated with different corresponding weather parameter. The results help recognize the vulnerability and resilience of future GB power systems to extreme weather events under different conditions.**

***Index Terms*—cooling systems, dynamic line rating, extreme weather, power systems, resilience, temperature effect**

I. Introduction

Power system, as one of the main critical infrastructures in a country, should not only be operated reliably under normal weather conditions, but also should be resilient against possible extreme weather events [1], such as those that can be attributed to climate change [2]-[4]. For instance, there were several extreme weather events (e.g., snow storm and flood) mentioned in [5], which all have led to customer disconnections and thus economic losses. In this light, as emphasized in [2] and [3], a framework for quantitatively assessing the resilience of future power systems, with the consideration of the vulnerability of various system infrastructures that will be exposed to the future climate conditions, is essential for the long-term system design and planning in terms of forecasting and mitigating potential ramifications of possible extreme weather events. In particular, this paper focuses on the impact of extreme temperatures and water availability.

To this end, it is important to firstly understand how extreme weather events, specifically in this paper extreme temperatures, and water availability can affect the overall resilience of power systems. On the one hand, the availability of the generation and transmission resources is affected by extreme temperatures; in addition, electricity consumption profiles may be shifted due to extreme temperatures (e.g., space cooling/heating demand). On the other hand, the water availability plays an important role in the determination of the usable capacity of power plants such as those using coal/gas/nuclear fuels, which require water cooling systems. More specifically, the existing literature on modelling and analyses of the above impacts are reviewed as follows.

A. Impact on generation system: water and energy nexus

The usable capacity of a thermoelectric power plant heavily relies on the temperature and availability of cooling water. This is because cooling water is required to absorb the wasted heat in order to maintain the security and efficiency of such type of power plants [6]. In this regard, few studies (e.g., [7]-[10]) have developed complex models that represent the relation between the usable capacity of a thermoelectric power plant and cooling water, taking account of the relevant fuel type, cooling system technology and water source.

In summary, the key conclusion from these studies is that for thermoelectric power plants, rising temperatures and reduction of water availability can threaten their cooling systems and thus undermine their usable capacities. For example, when the water temperature difference between inlet and outlet cooling water is under a certain level, more cooling water is needed so that the same waste heat can be discharged. If the water availability can afford the amount of the cooling water that is needed, the power plant can maintain a high usable capacity; otherwise, the usable capacity could be substantially undercut [8]. Consequently, the resilience of a power system whose main generation resource is thermoelectric power plants may be compromised in the case of extreme temperatures and insufficient cooling water.

B. Impact on transmission network

Similarly, extreme temperatures also affect thermal limits of the transmission lines. Basically, the conductor resistance of an overhead line is a function of the conductor's temperature that relates to different weather factors (e.g., ambient temperatures, wind flow, and solar radiation, etc.). In particular, the relation between actual current-carrying capacities of an overhead line and ambient temperatures was modelled in [11]-[13] taking account of the radiated and convective heat losses, respectively. In principle, the heat loss rate can decrease significantly following the decrease in the temperature difference between conductors and ambience. Thus, extreme ambient temperatures are able to undermine the capacity of an overhead line leading to potential impacts on the resilience of a power system. In

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addition, extreme temperatures can also increase the sag of an overhead line, resulting in clearance violations. However, this is out of the scope of this paper.

C. *Impact on electricity consumption profiles*

Besides, it is clear that extreme temperatures have key effect on the electricity consumption from space cooling and heating, e.g., air conditioning systems and heat pumps [14]-[16]. Thus, a cold winter day could lead to a high space heating demand from heat pumps, while a hot summer day causes high space cooling demand from air conditioning systems. In the latter case, it can be possible that the increase in electricity demand may coincide with the decrease in usable capacities of power plants, and thus weakening the resilience of a power system. This suggests that it is important to incorporate temperature-dependent load models into the assessment of power system resilience.

In addition to the impacts of extreme temperatures and water availability, other weather factors that can affect the resilience of a power system are also modelled in this paper. For example, the wind speed affects the vulnerability of overhead lines and towers, which can be modelled through their fragility curves [17]. Moreover, wind speeds, solar irradiances and tidal streams are the key factors to determine the available capacities of these renewable resources [18]-[19].

As seen above, various models and methodologies (e.g., [6], [8]-[13], [17] and [18]) have been developed to investigate the impacts of weather factors on individual infrastructures of a power system, instead of a system level resilience assessment. In this light, this paper has developed a framework for assessing the overall resilience of power systems highlighting impacts of extreme temperatures and water availability, and also taking proper account of other impacts, such as the vulnerability of overhead lines and towers and intermittency of renewable generation, etc. Afterwards, this framework is demonstrated on a reduced 29-bus GB system and the implications of extreme temperatures and water availability are inferred from the relevant simulation results.

The paper is organized as follows: Section II presents the proposed general framework for assessing the overall resilience of a power system with the consideration of different weather factors; the modelling approach used in this paper is discussed in Section III; Section IV applies the proposed assessment framework and modelling approach to a 29-bus reduced GB system with different scenarios particularly proposed for extreme temperatures and water availability. Finally, the general resilience implications of extreme temperatures and water availability and the significance of applying such an assessment framework are summarized in Section V.

II. Assessment Framework

This section presents the proposed framework for assessing the overall resilience of a power system. As seen in Fig. 1, this framework takes comprehensive account of the weather factors (e.g., ambient temperatures, wind speeds and solar irradiance), and the weather related factors (e.g., water availability and tidal stream), in terms of these factors' impacts on the resilience of a power system.

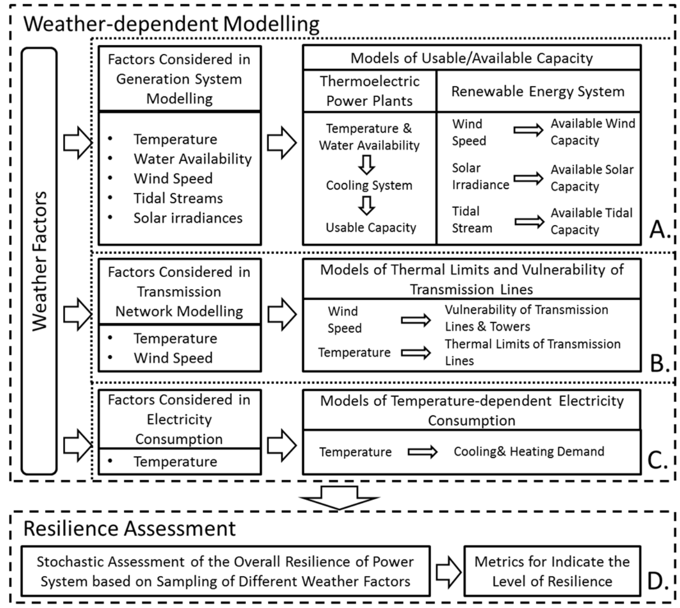

Fig. 1 Framework for assessing the overall resilience of a power system

For the generation system modelling, the usable capacity of a thermoelectric power plant is determined based on the ambient temperature and water availability; whereas, wind speeds, solar irradiances and tidal streams[1] are applied to obtain the available capacities of relevant renewable resources. With regard to the transmission network modelling, the ambient temperatures and wind speeds are used to compute the actual thermal limits of the overhead lines, while the wind speeds are also utilized to determine the vulnerability of overhead lines and towers. In terms of modelling the electricity consumption for cooling or heating, the ambient temperatures are the key input data. Afterwards, the models are used in a stochastic assessment of the overall resilience through sampling of the weather factors, as well as the failures of generators and overhead lines. Finally, different metrics are assessed to quantitatively indicate the resilience of the system under analysis.

III. Modelling Approach For Weather Factors

In this section, the key modelling approach for capturing the implications of air/water temperatures and water availability is introduced according to relevant impacts on generation system, transmission network and consumption profiles, respectively.

A. *Cooling system model for thermoelectric power plants*

A practical model for the cooling system is proposed in this section, which can be applied to the *Block A* in Fig. 1. Basically, a general and theoretical cooling system model was developed in [8] for the purpose of determining the usable capacity of a thermoelectric power plant based on the heat balance of the cooling system, as seen in (1) and (2).

$$q = P * \frac{1-\eta_{total}}{\eta_{ele}} * \frac{1-\alpha}{\rho * C_p * \max\left(\min\left(\left(T_{D\_max} - T_w\right), \Delta T_{max}\right), 0\right)} \quad (1)$$

$$P_{usable} = \frac{\min\left((Q), q\right) * \rho * C_p * \max(\min\left(\left(T_{D\_max} - T_w\right), \Delta T_{max}\right), 0)}{\frac{1-\eta_{total}}{\eta_{ele}} * \delta * (1-\alpha)} \quad (2)$$

[1] The tides can be affected by weather patterns, e.g., local onshore/offshore wind and air pressures [32]. However, this is not modelled in this paper.

In (1) and (2), q is the amount of cooling water required ($m^3 \cdot h^{-1}$); P is the installed capacity of the power plant (kW); C_p and ρ are the water heat capacity ($J \cdot kg^{-1} \cdot ℃^{-1}$)and density ($kg \cdot m^{-3}$), respectively; T_{D_max} is the maximum temperature of the outlet cooling water (℃); ΔT_{max} is the allowance of the maximum temperature difference between the inlet and outlet cooling water (℃); P_{max} is the relevant usable capacity (kW); Q is the water availability ($kg \cdot m^{-3}$); δ is a correction factor corresponding to the efficiency of thermal turbine and the cooling water when considering the efficiency reduction (%); α is share of waste heat not discharged by cooling water (%); η_{total} is total efficiency (%); η_{ele} is electric efficiency (%).

However, for the sake of simplicity and without the loss of generality, the aforementioned theoretical model in (1) and (2) is simplified based on some practical assumptions. To this end, the relevant assumptions are introduced and the new equations are derived accordingly in the following part.

First of all, in practice, Q depends on the actual environment and climate condition. In order to abstract the actual conditions, a cooling water scarcity factor (φ) is assumed to be the ratio of Q and q. Thus, if $\varphi > 1$, the water availability is sufficient, and vice versa. Secondly, two temperature thresholds (referred to as T_{health} and $T_{\text{shut-down}}$) are assumed for T_{w}. More specifically, it is assumed that if T_{w} is less than T_{health}, the usable capacity P_{usable} would be determined exclusively by the cooling water scarcity factor φ, as seen in (3). This implies that until T_{w} reaches T_{health}, the water availability dominates the impact on P_{usable}. When T_{w} becomes higher than $T_{\text{shut-down}}$, P_{usable} is considered to be zero as the cooling system is unable to provide its service.

$$P_{usable} = \min(\varphi, 1), \quad T_W \le T_{health} \quad (3)$$
$$P_{usable} = 0, \quad T_{shut-down} \le T_w \quad (4)$$

When T_{w} is inbetween T_{health} and $T_{\text{shut-down}}$, Q and T_{w} have an impact on P_{usable}. When $T_{\text{outlet\_max}} - T_{\text{w}} > \Delta T_{\text{max}}$, q would be a constant value according to (1). Thus, P_{usable} relies on the relation between Q and q, as well as the correction factor δ. A linear function is proposed in (5), where λ_{D} represents how fast P_{usable} decreases following the increase of T_{w}. Note that λ_{D} is conceptually equivalent to δ in (2). In addition, the impact of Q is represented by the front multiplier in (5). On the other hand, when T_{w} keeps increasing, $T_{\text{outlet\_max}} - T_{\text{w}}$ would become less than ΔT_{max}, leading to the significant increase of q according to (1). In this case, when $T_{\text{w}} > T_{\text{outlet\_max}}$- ΔT_{max}, it is assumed that P_{usable} would be affected only by the increase in the amount of required cooling water (q), thus a de-rating factor is applied in (6) in order to determine P_{usasble} based on the P_{usasble} when T_{w} = $T_{\text{outlet\_max}}$- ΔT_{max} as seen in (6).

$$P_{usable} = \min(\varphi, 1) \cdot \left(1 - \lambda_D (T_w - T_{health})\right), \quad T_{health} \le T_w \le T_{outlet\_max} - \Delta T_{max} \quad (5)$$
$$P_{usable} = \frac{T_{outlet\_max} - T_w}{\Delta T_{max}} \cdot \min(\varphi, 1) \cdot \left(1 - \lambda_D \left(T_{outlet\_max} - \Delta T_{max} - T_{health}\right)\right), \quad T_{outlet\_max} - \Delta T_{max} \le T_w \le T_{shut-down} \quad (6)$$

For modelling open-loop cooling systems, the model in (3) to (6) could properly capture the impact of the inlet cooling water temperature and the water availability. For example, assuming $T_{\text{outlet\_max}}$=35 °C; ΔT_{max}=10 °C; $T_{\text{shut-down}}$=32°C; T_{health}=15 °C; φ is 1.2 for straight line and 0.7 for dotted line; λ_D=0.444. Fig. 2 shows the usable capacity as a function of inlet water temperature.

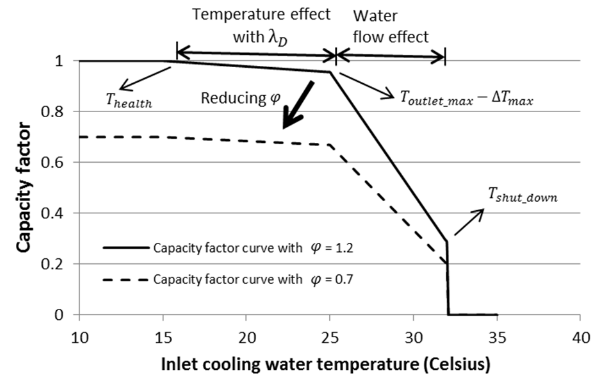

Fig. 2: Example of capacity factor curves for open-loop cooling plant

In terms of closed-loop/hybrid cooling systems, the cooling water is circulated in closed-loop and the loss of cooling water is only about 2%-4% of the inlet cooling water that is consumed by open-loop cooling systems. Thus, the water availability has negligible effect on closed-loop/hybrid cooling systems [9]. In this case, the model in (3) and (5) is applied to represent closed-loop cooling systems, by assuming a very high $T_{\text{outlet\_max}}$ and in addition, φ is considered to be 1.

B. *Dynamic Thermal Rating of Transmission Lines*

The dynamic thermal rating model that was developed in the IEEE Standards Association [20] is applied to capture the effect of ambient temperatures and wind speeds on the actual capacity of an overhead line. This model fits into *Block B* in Fig. 1. More specifically, the actual capacity of an overhead line is expressed as a function of the ambient temperature and wind speed based on the steady- state heat balance, as in (7) to (10).

$$q_c + q_r = q_s + l_{rating} \quad (7)$$
$$q_c = k_{angle}[1.01 \times 1.35 \times N_{RE}^{0.52}] \times k_f \times (Ts - Ta) \quad (8)$$
$$q_r = 17.8 D_0 \varepsilon \left[\left(\frac{T_s + 273}{100}\right)^4 - \left(\frac{T_a + 273}{100}\right)^4\right] \quad (9)$$
$$N_{RE} = \frac{D_0 p_f v_w}{u_f} \quad (10)$$

Where q_c is the convection heat loss rate ($W \cdot m^{-1}$); q_r is the radiated heat loss rate ($W \cdot m^{-1}$); q_s is the heat gain rate ($W \cdot m^{-1}$) from the sun assumed as constant in modelling; l_{rating} is the thermal limit of conductor (MVA); k_{angle} is the wind direction factor; Ts is the conductor surface temperature (℃); Ta is the ambient temperature (℃); k_f is the thermal conductivity of air ($W \cdot m^{-1} \cdot ℃^{-1}$); D_0 is the conductor diameter (m); ε is the emissivity; p_f is air density ($kg \cdot m^{-3}$); v_w is wind speed ($m \cdot s^{-1}$); u_f is the dynamic viscosity of air ($kg \cdot m^{-1} \cdot s^{-1}$).

In the case study that is presented in Section IV, it is assumed that the conductor surface temperature is 75 °C; the conductor diameter is 20 mm. The ambient temperatures and wind speeds are sampled in Section IV, while the values of the rest factors are obtained from [20] according to the sampled temperatures.

C. *Temperature-Dependent Future Demands*

The temperature-dependent demand model presented in [18] is used for *Block C* in Fig. 1. The demand profile in 2010 is used to develop the baseline for both winter quarter and summer quarter, which are divided into several demand sectors [14]. Fig. 3 demonstrates an example of the demand profile of a summer weekday, disaggregated into various customer sectors.

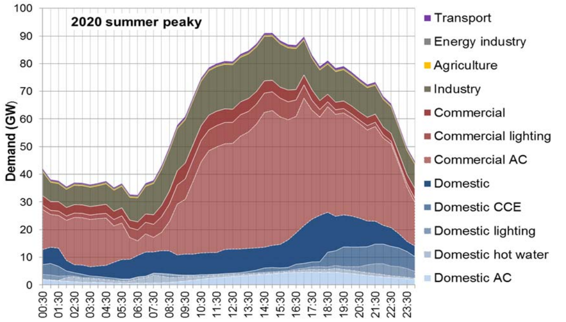

Fig. 3: Example of 2020 summer quarter weekday peaky demand profile.

As mentioned in Section I-C, temperatures have an increasing impact on the electricity consumption due to the electrification of space heating and cooling. The temperature would directly affect the electrical demand in the customer sectors, such as Commercial and Domestic AC in summer as seen in Fig. 3. The detailed modelling approach can be found in [21].

D. Computational Approach for the Resilience Assessment

As used in [22]-[24], the Sequential Monte Carlo Simulation (SMCS) is suitable to capture the spatial and temporal features of weather events. Thus, the SMCS is adopted in the resilience assessment (see *Block D* in Fig. 1).

IV. Case Studies

The case study here applies the proposed framework to a 29-bus reduced GB power system, with the key aim to demonstrate the impacts of extreme temperatures and water availability on the level of the system resilience.

The 29-bus reduced GB power system is illustrated in Fig. 4, which has 29 nodes, 99 transmission lines and 50 corridors. The generation portfolio is used in accordance with the generation scenario proposed by the Resilient Energy Networks for Great Britain (RESNET) project [25]. The SMCS and regional weather profiles enable a temporal-spatial simulation. Additionally, an AC-OPF framework is utilized to evaluate the performance of power system operation with hourly step via the MATPOWER. In terms of reliability indices, Loss of Load Expectation (LOLE), Loss of Load Frequency (LOLF) and Expected Energy Not Supplied (EENS) are assessed to indicate the resilience of the system. Note that the studied period covers a whole week (168 hours) that includes the annual peak day.

A. Weather Regions

For the sake of simplicity and without loss of generality, the 29-bus reduced GB power system (as seen in Fig. 4) is assumed to be divided into several weather regions, so as to include the spatial-temporal weather impact on the system. Then, the same weather condition is homogenously assumed in each region at every simulation step.

According to Fig. 4-a, six wind regions are assumed for the test system, while the typical nine regions of England, Wales and Scotland (i.e., 11 regions in total) are assumed for the solar irradiance [18]. Additionally, three regions are assumed for the temperatures, i.e., Edinburgh (E), Manchester (M) and Slough (S), corresponding to Scotland, Northern and Southern England respectively.

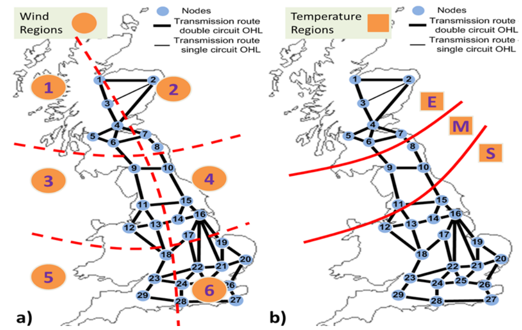

Fig. 4: a) 29-bus reduced GB power system with six wind regions; b) three temperature regions (Edinburgh, Manchester and Slough)

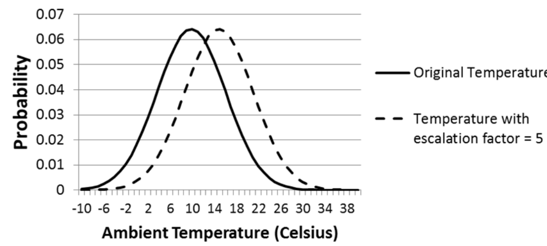

Fig. 5: Example of the escalation of temperature profiles

B. Scenarios for Extreme Temperatures

The temperature profiles for the three temperature regions in Fig. 4-b) are acquired from the UK Climate Projections [26]. In order to create extreme temperatures, the new temperatures are obtained by increasing the original temperatures by a constant escalation factor, for instance 5 °C as seen in Fig. 5, where the probability distribution of the original temperatures in the same temperature region and the one after escalating.

C. Scenarios for Different Water Condition

There is no explicit relation between water availabilities and ambient temperatures [27]. In order to show the impact of water availability on the power system resilience, the following water availability scenarios are proposed and listed in Table I, which are rainy, wet, normal, dry and extreme. It is worth mentioning that due to the lack of time series of water availability data, the water scarcity factor (φ), as defined in Section III-A, is applied to create water availability scenarios. Besides, φ is assumed to reduce linearly following the increase of ambient temperature, reflecting the increasing severity of water scarcity due to high temperature events. Besides, each water availability scenario is studied under nine levels of temperature boost from 0°C to 16°C with steps of 2°C. Though these are scenarios for the sake of demonstration, the results are of general validity in terms of the implications of extreme temperatures and water availability.

Moreover, the efficiency reduction factor λ_D in (1) varies with fuel types and cooling technologies of the thermoelectric power plants. According to [7], [9], [10], [28] and [29], the values used in the case study are presented in Table II.

TABLE I
FIVE WATER AVAILABILITY SCENARIOS

Scenario Name	Water scarcity factor (φ)			
	T_{air} < 10°C	T_{air} ϵ [10,20]	T_{air} ϵ [20,30]	T_{air} ϵ [30,40]
Rainy	2.0	1.6	1.2	0.8
Wet	1.8	1.4	1.0	0.6
Normal	1.6	1.2	0.8	0.4
Dry	1.2	0.8	0.4	0.2
Extreme	0.8	0.4	0.2	0.2

TABLE II
THERMOELECTRIC GENERATION DE-RATED RATE PER DEGREE CELSIUS WITH INCREASING TEMPERATURE

Type	Nuclear	Fossil-fueled	Fossil-fueled	Natural Gas
Cooling Method	Open-loop	Open-loop	Closed-loop	Open-loop
λ_D(%)	0.444	0.350	0.320	0.650
Type	Natural Gas	CCGT	CCGT	OCGT
Cooling Method	Closed-loop	Open-loop	Closed-loop	Closed-loop
λ_D(%)	0.620	0.970	0.940	0.920

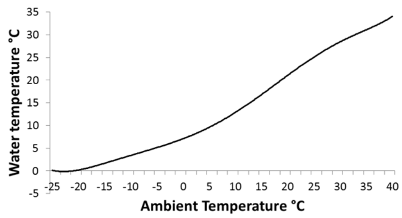

Fig. 6: Generic curve for water and ambient temperature conversion

Furthermore, for the sake of simplicity and without losing generality, a relationship of the ambient and water temperature is approximated based on the statistical data in [30] and [31], as seen in Fig. 6. This approximation provides the inlet cooling water temperature that is, to a certain extent, in consistent with the ambient temperature. This can reveal the general impacts of extreme temperatures with a reasonable accuracy.

D. Simulation Results

The results that are assessed for the above water availability scenarios and different levels of temperature boost are shown in Figs. 7, 8, 9 and 10. In Figs. 7, 8 and 9, the resilience level of the GB system indicated by LOLE, LOLF and EENS respectively, is expressed as functions of the maximum temperature occurred in the weather profile. It is seen clearly that the GB system can maintain a good level of resilience until the maximum ambient temperature of 35 °C[2]. Afterwards, the resilience level starts to decrease as shown by the sharp increase of LOLE, LOLF and EENS. This is because, according to Fig. 6, when the maximum ambient temperature becomes greater than 35 °C, water temperatures in many hours would exceed the temperature threshold ($T_{\text{outlet\_max}} - \Delta T_{\max}$) in Fig. 2, leading to a substantial decrease in the total usable thermal capacity or even plant shut-downs. In addition, high temperatures can increase the cooling demand and undercut thermal limits of overhead lines. This may further exacerbate the situation faced by the system.

In addition to the impact of extreme temperatures, the impact of water availability can also be seen in Figs. 7, 8 and 9, i.e., the more sufficient the water availability, the better the resilience level when being exposed to the same temperature condition. In order to provide more insights, Fig. 10 presents the resilience level (also indicated by LOLE, EENS and LOLF) as functions of the water availability represented by water scarcity factor φ, with the same temperature condition. It is shown clearly that increasing the water availability could make the system substantially more resilient against high temperatures, and vice versa.

[2] Note that these temperatures are used for demonstrating the developed assessment framework, in order to model a wide range of weather conditions including the extreme temperatures that could occur in Great Britain.

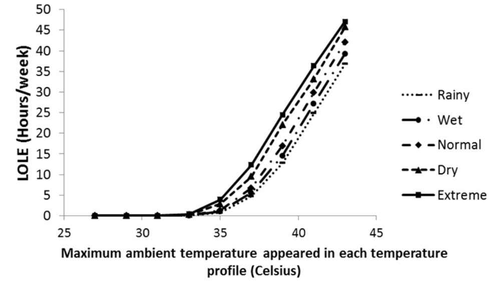

Fig. 7: LOLE as the function of the maximum ambient temperature appeared in GB in each temperature profile

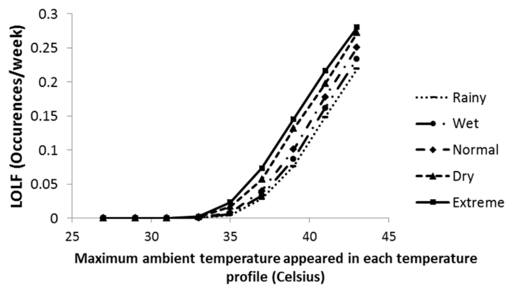

Fig. 8: LOLF as the function of the maximum ambient temperature appeared in GB in each temperature profile

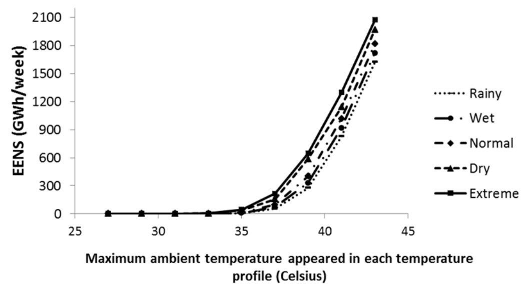

Fig. 9: EENS as the function of maximum ambient temperature appeared in GB in each temperature profile

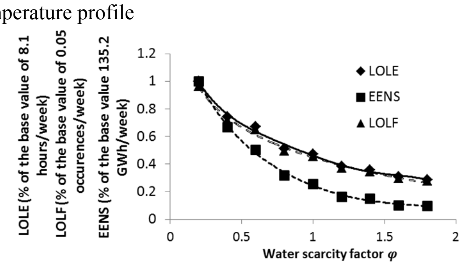

Fig. 10: LOLE, LOLF and EENS as the function of water scarcity factor

On the one hand, the inland thermoelectric power plants rely on fresh water as the cooling water source. This means that it is more likely for them to face scarcity of cooling water, and thus they become vulnerable to extreme high temperatures. On the other hand, for the ones along the coastal areas, they can extract sea water for their cooling systems, so that they would be more resilient against extreme high temperatures due to the sufficient supply of cooling water.

It is also worth mentioning that the extreme temperature has greater impact than the water availability, as observed in Figs. 7, 8 and 9. This is because the extreme temperature not only can undermine the usable capacities of thermoelectric power plants and thermal limits of overhead lines, but also might increase the consumption (as obtained by the temperature-dependent demand profiles); whereas, the water availability only relates to the usable capacity.

V. Conclusions

This paper has proposed a general framework for assessing the overall resilience of a power system, taking into account the implications of various weather factors, in particular extreme temperatures and the water availability. This framework is based on a time-series modelling approach, which specifically accounts for the temperature sensitivity and the impact of water availability on the cooling systems of all conventional thermal power plants, as well as the temperature sensitivity of overhead line capacities and of electrical demand throughout the network. In general, it can be concluded that the extreme high temperatures can undermine the usable capacities of conventional thermal power plants and the thermal limits of overhead lines, while as well increasing the electrical demand. Hence, the overall resilience level would be deteriorated. Nevertheless, sufficient water availability can make the system more resilient against high temperatures by preserving the usable capacities of thermoelectric power plants. More importantly, in order to take proper account of the interactions of extreme temperatures, the water availability, the usable capacities, the thermal limits and the electrical demand, etc., it is essential to have a systematic and comprehensive resilience assessment framework as the one proposed here.

Future work aims to conduct a techno-economic assessment for the integration of storage facilities and demand response for the purpose of enhancing power system resilience, as space cooling and heating demand are highly affected by extreme temperatures.

Acknowledgement

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