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► To cite this version:

Damien Raynaud, Benoit Hingray, Baptiste François, Jean Dominique Creutin. Energy droughts from variable renewable energy sources in European climates. Renewable Energy, 2018, 125, pp.578-589. 10.1016/j.renene.2018.02.130 . hal-02327441

HAL Id: hal-02327441 https://hal.science/hal-02327441v1

Submitted on 26 Nov 2020

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1	Energy droughts from variable renewable energy sources				
2	in European climates				
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19 Abstract

The increasing share of variable renewable energy sources in the power supply system raises questions about the reliability and the steadiness of the production. In this study, we assess the main statistical characteristics of "energy droughts" for wind, solar and run-of-the-river hydro power in Europe. We propose two concepts of energy droughts, considering either: Energy Production Droughts (EPD) as sequences of days with low power production or Energy Supply Droughts (ESD) as sequences of days with a high production/demand mismatch.

26 Using a set of adhoc weather-to-energy conversion models, we characterize energy droughts in 12 European regions from 30-yr series of daily wind, solar, hydro power and energy 27 demand. The characteristics of EPD are very different between sources with short but frequent 28 wind power droughts and rare but long hydro power ones. Solar power droughts are very region-29 dependent with much longer droughts in Northern Europe. ESD are next characterized in a 100% 30 renewable energy scenario. The features of EPD and ESD differ significantly, highlighting the 31 interplay with the energy demand. Moreover, both duration and frequency of energy droughts 32 decrease when mixing energy sources or when some storage capacity balances the temporal 33 production / demand mismatch. 34

35

Keyword: Energy droughts; Variable renewable energy; Energy demand; Hydro-climatic
 variability; Europe; Wind, Solar; Hydropower

38 1. Introduction

During the 21st Conference of Parties (COP21), the 2015 United Nations Climate Change 39 Conference in Paris, , 175 countries agreed on limiting the temperature increase due to global 40 warming to 2°C above preindustrial levels. Such an ambitious goal necessitates a deep 41 transformation of our societies and first and foremost a reduction of the anthropogenic 42 greenhouse gas emissions. Many countries have already started their energy transition. In Europe, 43 44 increasing the share of renewables in the electricity production mix is one of the main targets for the next decade. The European Climate Foundation even set a 100% renewable mix objective to 45 be met by 2050 [1]. In Europe, just like in most regions worldwide, this goal is at least physically 46 realistic, since the resource in renewable energy balances the energy demand several times [2]. 47

Variable renewable energies (VRE) and especially those driven by weather, namely wind, 48 solar and hydro-power from river flow, are expected to play a key role in increasing the share of 49 renewables. Indeed, the installed capacity of VRE is quickly growing worldwide [3]. Exploitable 50 roughly everywhere, wind and solar resources are, for instance, already important contributors of 51 the energy mix in Europe. For some countries, they largely contributed to the early achievement 52 of the 27 % share of renewables targeted for 2030 by the European Council [4]. Hydropower 53 54 from river flow, classically obtained from run-of-the river power plants (further referred to as 55 RoR power plants), is often given less consideration, especially when compared to the key role of hydropower from large water reservoirs [5]. Even if individual RoR plants have fairly no 56 balancing capacity and only small to very small power capacity (e.g. often smaller than a few 57 MW), the overall RoR production is far from negligible in some regions [6][7]. It is also expected 58 to increase significantly in the next years worldwide with the construction of new plants, the 59 60 upgrade of old ones and the deployment of new technologies such as river hydrokinetic turbines [8][9]. 61

Wind power, solar power and hydro-power from river flow are by definition very sensitive to weather conditions, and thus present high space/time variability [10]. Moreover, wind and solar power are highly intermittent. Consequently, the integration of VRE in the power system is often difficult. They also make power systems rather vulnerable to the hydro-climatic variability and hydro-meteorological extreme events. These issues become even more critical for high shares of VRE [11][12].

In the last decade, many studies have focused on the intermittency of VRE production at 68 small time scales [13][14][15]. These fluctuations result from the strong variability of weather 69 variables and, to a lower extend, from the cut-in and cut-off thresholds of power generators that 70 only function for a specific range of meteorological conditions (e.g. wind-speed based cut-in and 71 72 cut-off thresholds for wind turbines). Covering timescales ranging from seconds to several hours, these high-frequency variations in power production lead to a number of critical operational 73 issues (e.g. maintaining the system's stability in order to avoid the system collapse). This 74 especially calls for the support of sufficient mechanical inertia in the system, fast responding 75 back-up power and flexible storage facilities as well as demand-side management [16]. 76

Low VRE production conditions can be also problematic. They result from weather or hydrometeorological configurations with low VRE resources or from situations for which a production curtailment is necessary to avoid damage on power production units (e.g. when wind speed exceeds the cut-off threshold of wind turbines). They can induce critical situations in term of reliability of the power supply potentially and require the use of large back-up sources or 82 energy storage facilities [17][18]. Low VRE production conditions have been the centre of 83 attention of numerous studies. They either aim to assess the risks related to low production 84 sequences, in terms of probability of occurrence or duration for both current and future climate 85 conditions, or to improve their predictability, with the objective of supporting the operational 86 management of transmission system operators and guarantee system reliability.

Low river flows affect the hydropower production and a number of other water-related 87 systems. Consequently, a large number of studies focused on the characterization of these 88 conditions in terms of occurrence, durations and severity from local to continental scales (e.g. 89 [19] for the European domain). A lot of effort is also made to improve their predictability from 90 daily to seasonal scale [20][21]. The persistence of wind calms and/or the characteristics of low-91 wind speed periods (for various thresholds) have been similarly analysed for a number of sites 92 worldwide [22][23][24]. Recent studies also consider the occurrence of simultaneous low wind 93 conditions across large areas in the context of modern transmission grids [25][26][27]. Similarly, 94 low solar power periods due to overcast conditions, persistent low level clouds or dust outbreaks 95 have been recently analysed [28][29][30]. 96

97 The impact of low VRE production periods is also likely to be increased if they co-occur 98 with high energy demand [31][32][33], a situation which can result from the fluctuation of some 99 large scale climate phenomenon such as the North Atlantic Oscillation [34].

100

101 In this study, we propose to complement and enlarge these analyses by characterizing and comparing the periods of low VRE production in Europe for the three main renewable power 102 sources, namely wind, solar and hydro power from river flows. We consider the three sources 103 separately and also combined in an energy mix. For the three sources, we use a same analysis 104 framework and focus on what we call "energy droughts" whose concept rests on the analogy with 105 106 the classical hydro-meteorological droughts, defined as long periods of very low river flows [22] or periods with no or fairly no precipitation [35][36]. We here propose two definitions of "energy 107 droughts", considering either 1) Energy Production Droughts as uninterrupted sequences of days 108 with low power production or 2) Energy Supply Droughts as uninterrupted sequences of days 109 with a high production/demand mismatch. We here characterize Energy Supply Droughts within 110 a hypothetical 100% VRE system where electricity generation comes from wind, solar and/or 111 run-of-the-river hydro-power only. We do not base our analysis on site measurements but on high 112 113 resolution gridded hydrometeorological datasets obtained for a 30-year historical period from satellite observations and from outputs of weather and hydrological models. This allows us to 114 conduct our study on different European regions (12) and thus explore how the characteristics of 115 energy droughts also depend on the climatic spatial variability. 116

117 The meteorological datasets and the different weather-to-energy conversion models are 118 presented in section 2 together with the two definitions of energy droughts. Section 3 gathers the 119 results of this study and a comparison of the two droughts definitions. The results are discussed in 120 Section 5 and section 6 concludes our study.

121 **2.** Datasets and models

122 2.1 Hydro-meteorological data

We consider twelve regions homogeneously spread over Europe and Maghreb and having a surface area of about 40000km² (**Fig.1**). As discussed in François et al. [12], they draw a picture of the large variety of climatic conditions existing in Europe with four main influences: a North-South gradient from Scandinavian to Mediterranean climate and a West-East contrast from

127 Oceanic to continental influences.



128

129 Fig.1: Locations and boundaries of the 12 test regions. The two letters are further used as regional IDs.

130 Several meteorological variables are required to simulate electricity production and demand time series. Temperature and precipitation data are based on on-site measurements and 131 are extracted from the European Climate Assessment & Dataset (ECAD, [37]) at a daily time step 132 133 and on 0.25 degrees grid spacing. Solar radiation series comes from the Surface Solar Radiation Dataset - Heliosat (SARAH) which relies on satellite measurement [38]. It has a 0.05° grid and 134 data are also extracted on a daily basis. Finally, we use pseudo-observations of wind speed 135 derived from simulations of the Weather Research and Forecasting Model which has been forced 136 by the ERA-Interim reanalysis [39]. All these data are available on a 30-yr long research period, 137 138 extending from 1983 to 2012.

River discharges are highly regulated in most regions of Europe. In order to free ourselves from this anthropogenic influence and only depend on the hydro-climatic variability, we use unregulated discharge estimates. They are obtained with a distributed version of the GSM-Socont hydrological model [40] on a 0.25° grid from each test region [12]. Using the previous precipitation, temperature, and wind speed series, this model simulates the main hydrological processes which drive river discharge (e.g. snowpack dynamics, evapotranspiration, infiltration, runoff transfer).

146 **2.2 Weather-to-energy conversion models**

Daily time series of solar, wind and RoR power are simulated from weather and river discharge thanks to "weather to energy" conversion models. These models are based on generic production systems obtained from generic wind turbine, photovoltaic panel or RoR plant. For each energy source, we assume that all grid cells of the considered region have the same level of equipment. The overall regional production is obtained by summing the simulated production values of all grid cells.

For each grid, solar power (P_{PV}) time series is derived from global solar irradiance I_{eff} 153 (Wm⁻²) and air temperature T_a (°C) following Perpiñan et al. [41]. The conversion of wind speed 154 into wind power relies on a two-step process. Firstly, the 10m wind speed series are extrapolated 155 to 80m (height of the generic turbine hub), assuming a logarithmic increase in wind speed with 156 increase in altitude. Daily wind speed is then converted into wind power with the idealized power 157 curve described in Francois et al. [12]. To estimate RoR hydro power from river discharge P_{RoR} 158 159 (kW), we use a classic conversion function (Eq.1) using the water head h (m) defined as the 160 altitude difference between the current grid cell and the lowest point of the region.

$$P_{RoR}(t) = \eta_H gh\rho q(t) \tag{1}$$

161 where η_H the efficiency of the turbine (%), q the flow passing through the turbine 162 $(m^3. s^{-1})$, g the acceleration of gravity (=9.81 $m. s^{-2}$), ρ the water density (=1000 kg. m^{-3}). The 163 water flowing through the turbine is modelled as a non-linear function of the river discharge as 164 described in Francois et al. [12]. The local runoff produced in any given grid is assumed to be 165 ideally harnessed from its location of origin to the catchment's outlet.

166 The daily energy load required here to analyse the Energy Supply Droughts is finally 167 estimated for each grid cell from daily temperature (**Eq.2**). Thus, we put aside all non-weather 168 related influences on the demand, and only focus on the effects of temperature fluctuations. In 169 this way, results from different regions are easily comparable whatever the population or their 170 economic development. The daily energy load L (Wh) is estimated as:

$$\begin{cases} L(t) = a_{T_{Heat}} \times [T_{Heat} - T(t)] + b \ if \ T(t) < T_{Heat} \\ L(t) = 1 \ if \ T_{Heat} < T(t) < T_{Cool} \\ L(t) = a_{T_{Cool}} \times [T(t) - T_{Cool}] + b \ if \ T(t) > T_{Cool}, \end{cases}$$
(2)

171 where T_{Heat} and T_{Cool} are the heating and cooling thresholds (15°C and 20°C respectively), 172 *b* (Wh) is the base load for the temperature-independent range and a_{Theat} (Wh °C⁻¹), a_{TCool} (Wh °C⁻¹) 173 ¹) are the weather sensitivity coefficients for heating and cooling respectively. The parameters 174 were estimated using observed data of electricity demand from the European Network of 175 Transmission Systems Operators of Electricity (ENTSOE, <u>https://www.entsoe.eu/home/</u>) (more 176 details in François et al. [12]).

177 **3. Definition of energy droughts**

178 **3.1 Energy Production Droughts (EPD)**

We define a low production period as a contiguous sequence of days during every day of which the production is below a given low-production threshold. This analysis requires the calculation of a daily Deficiency Index (DI) time series for each region and energy source. The 182 DI time series simply reduces the power production to a binary time series equals to 0, when the 183 daily production (P) is greater than the low-production threshold (P_0), or to 1 when lower (**Eq.3**).

184 $DI(i) = 1 \text{ if } P(i) \le P_0$

(3)

185 DI(j) = 0 if $P(j) > P_0$

In our case, the threshold is set to a given percentage of the mean daily production estimated over the whole period of analysis, i.e. 1983-2012. The duration of a low production period is defined as the number of consecutive days for which the DI index equals 1 (**Fig.2a**).

Our definition is different from the one classically used for the analysis of hydrological droughts. In the latter case, the threshold changes periodically in time and usually corresponds to a given percentile of observed discharge data (e.g. the 90% percentile). It is usually estimated by using a moving seasonal window and all available observations falling within [42][43]. In our study, the threshold is time-invariant. Thus, droughts events are defined per-se and not as events that are unusual when compared to a calendar climatology. This definition allows the comparison of droughts regimes and severity obtained for different energy sources or different regions.

We will consider in turns two thresholds which correspond respectively to 0.2 and 0.5 times the mean daily production of the considered region/VRE source. We will refer to the corresponding low productions as moderate and severe "Energy Production Droughts" respectively (EPD in the following).

EPD are defined with respect to the mean daily production obtained for the considered region. They are thus defined per-se and do not depend on the electricity demand. Hence, they only represent a signature of weather and hydrometeorological variability.

3.2 Energy Supply Droughts (ESD)

As mentioned in Section 1, the severity of "energy droughts" can be reinforced (resp. reduced) if they occur during higher (resp. lower) than usual demand periods.

An impact oriented assessment of energy droughts leads to consider Energy Supply 206 Droughts, where the production/demand (im-)balance is accounted for. For the present analysis, 207 we account for the production/demand (im-)balance that would be obtained for each region 208 individually. We thus consider that each region is "autonomous", i.e. that there is no energy 209 exchanges with the neighbouring regions. We further consider that all the regional production 210 comes from solar, wind and/or RoR hydro power only and that the 30-yr mean regional VRE 211 212 production equals the 30-yr mean regional electricity demand. This configuration corresponds to the so-called 100 % renewable scenario considered in a number of recent works (e.g. [11][12]). 213 We finally use the "copper plate" assumption within each region and thus consider that there is 214 no energy transmission limitation within each region. 215

We here also define what we will refer to as low satisfaction periods, as sequences of days for which the non-satisfied demand is greater that a given fraction k of the mean electricity demand. This analysis also requires the calculation of a Supply Deficiency Index (SDI) time series for each energy source and region. This index is estimated on a daily basis as following (**Eq.4**):

(4)

221
$$SDI(j) = 1 \text{ if } (D(j)-P(j)) > k.D_m$$

222 SDI(j) = 0 if otherwise

Where D(j) is the energy demand on day j, D_m is the mean daily energy demand over the whole 1983-2012 period. The main characteristics of low satisfaction periods are derived from the time series of the SDI index similarly to what has been described for Low Production Periods in Section3.1 (see **Fig.2b**). We consider two thresholds values, k=0.5 and k=0.8, which correspond to what we will call moderate and severe Energy Supply Droughts respectively (ESD in the following).

The DI and SDI indices are very similar. Actually, the DI index corresponds to the SDI index for which the electricity demand would be constant in time and equals to the mean production D_m . In our case, it is easy to show that the thresholds considered for the definition of moderate EPD and moderate ESD refer to a same drought intensity level. The same applies to severe EPD and severe ESD. Thus, moderate (resp. the severe) droughts, can be compared for both definitions, making possible to estimate how the production/demand co-variability structure influences the characteristics of energy droughts.

A visual comparison between the two definitions of energy droughts is presented for one year-long time series of simulated hydro power production and energy demand on **Fig.2**.

Electricity production droughts

238

2 Electricity production 1.5 1 0.5 0 50 0 100 150 200 250 300 Time (days) Electricity supply droughts Electricity production and demand 0 50 1 51 5 100 150 Ó 50 200 250 300 Time (days)

239

Fig.2: "Energy Production Droughts" (a) and "Energy Supply Droughts" (b). Illustration for one year of hydropower power production (blue) and energy demand (black) in England. Production and demand time series have been normalized so that the annual average equals 1 for both series. Energy Droughts sequences correspond to the grey shaded bars. In (a) droughts correspond to a production smaller than 0.2 times the mean annual production. In (b) droughts correspond to a difference between demand and production greater than 0.8 (in this configuration the production falls below the dotted line which is

246 defined from D(j)-0.8 D_m). These two configurations correspond to the definition of what we call "severe" 247 droughts.

248 **4. Results**

For the different energy sources, we now describe the number of days with low production and present the characteristics of EPD and ESD. Some figures only gather information for 3 regions (Norway (NO), Germany (GE), Andalucía (AN)) which draw a rather representative picture of energy droughts features for Europe.

253 4.1 Days in drought state

Fig.3 presents the cumulative distribution functions (cdfs) of daily power production simulated for wind, solar and hydro power in NO, GE and AN. To make the comparison between energy sources easier, the times series have been scaled dividing them by the mean daily production over the whole 1983-2012 period. The two dashed lines represent the 0.5 and 0.2 thresholds used to identify the days in a moderate or severe drought state respectively.

Wind power classically exhibits the larger range of daily production values with heavytailed cdfs (e.g. in GE and AN). The proportion of days in a moderate drought state is rather similar between regions and of about 35%. Conversely, regional differences are much higher for days in a severe drought state with much fewer days in southern Europe (here in AN).

The variability of daily solar power production and the proportion of days in drought state are much higher in Northern Europe than elsewhere. This is obviously a direct consequence of the latitude influence on the space/time daylight variations in Europe. About 25% and 40% days are for instance below the severe and moderate thresholds respectively in NO while only few days are in drought conditions in AN (about 1% for the severe droughts threshold and 10% for the moderate drought one).

269 For hydropower, the cdf of daily production can have very different shapes from one region to the other. They have similar shapes in Alpine areas, Northern and southern European 270 regions (here NO and AN) with a large proportion of days below the drought thresholds (15% 271 272 below the 0.2 threshold and about 30% below the 0.5 one). In high elevation or high latitude regions, these days often occur in winter as a result of the typical snow-dominated hydrological 273 regimes of river basins (not shown). The cdfs of hydro power production present less skewness in 274 275 regions located in plains (here GE), leading to much smaller numbers of days in drought conditions. 276





Fig.3: Cumulative distribution functions (cdfs) of normalized power production for each VRE
 source in 3 European regions. Hydro – blue, Wind – orange, Solar – red. See Fig.S1 for results on all 12
 regions

281 4.2 Energy Production Droughts

The characteristics of EPD also depend on the energy source and on the region. Fig.4 282 gathers, for the 12 European regions, the mean duration (x axis) and the mean annual frequency 283 284 (y axis) of energy droughts. Additionally, the background colour scale gives the proportion of days under drought conditions discussed in Sec.4.1. With this representation, all points located on 285 a descending diagonal and for a fixed background colour present the same number of drought 286 days. The representation also makes possible to differentiate configurations with numerous but 287 288 short droughts (points located in the left/upper side of the diagonal) from situations with rare but long lasting ones (points located in the right/bottom side of a given diagonal). 289



290

Fig.4: Annual frequency (y-axis) versus mean drought duration (x-axis) of Energy Production Droughts (EPD) for (top) moderate and (bottom) severe droughts. The colour shade gives the proportion of days experiencing energy drought conditions within the 30-year period (wind: orange; solar: red; hydro: blue). All points located on a descending diagonal at a chosen colour present the same number of days in drought conditions. The ID of each region is indicated within each dot.

296

This representation gives a synthetic but partial picture of drought characteristics. The characteristics of individual drought sequences (e.g. duration and intensity) may obviously differ greatly between events. For illustration, **Fig.5** presents the cdfs of the droughts durations obtained for severe and moderate EPD in the NO, GE and AN regions. In the following analysis, this variability should be kept in mind.



302

Fig.5: Reverse cumulative distribution of the duration of Energy Production Droughts for both moderate (top: 50% level) and severe (bottom: 20% level) droughts in NO, GE and AN. Hydro power droughts (blue); wind power droughts (orange), solar power droughts (red). All panels show the percentage of drought events of the 30-yr period that exceed a given duration in days. See Fig.S2.a and FigS2.b for results on all 12 regions.

For both moderate and severe droughts, the homogeneity of wind power EPD 308 characteristics is noteworthy: all individual droughts have very short durations (1 to 7days -309 Fig.5). The main characteristics of moderate wind power EPD are also very similar from one 310 region to the other (Fig.4). Indeed, whatever the region, moderate droughts are numerous (from 311 312 50 to 60 events per year) and last from two to three days in average. The mean duration of severe wind droughts, smaller than 2days, is also very similar between regions. Conversely, their 313 314 frequency is more variable with fewer droughts sequences in the Mediterranean regions. This result induces a much lower number of days in severe drought conditions for these regions. 315

Hydropower droughts are rather rare (less than 5 events per year). Individual hydropower 316 droughts also present a large diversity of duration with relatively short episodes to extremely long 317 ones which can last several months (Fig.5). Conversely to wind EPD, short events (up to a few 318 days) represent a small proportion of hydro-power droughts. Indeed, the hydrological processes 319 and underground storage capacity of river basins work as powerful low-pass filters and ease most 320 of the daily meteorological variability. The characteristics of hydropower droughts depend a lot 321 on the region (Fig.4). The longest droughts are found in Scandinavian and Mediterranean 322 regions. In NO and AN, hydropower droughts can last up to 5 months. However, these EPD 323 occur in different seasons: in summer in TU, AN and GR, in winter in NO, IT and FI (not 324 325 shown). They respectively result from long periods with no or few precipitation and, for high elevation/latitude regions, from the storage in snowpack of most winter precipitation. Finally, the
characteristics of hydropower droughts also significantly depend on the drought intensity level.
Severe hydropower EPD are roughly twice less numerous than moderate ones. They also last
30% to 50% time less. The regional specificities are roughly the same for both drought intensity
levels.

The characteristics of solar droughts are in-between those of wind and hydropower 331 droughts (Fig.4). The number of solar drought events is medium in all regions. However, there 332 are two different types of droughts with on one hand very short events, and on the other hand 2 to 333 3 months EPDs (Fig.5). Short events correspond to cloudy weather situations, which mainly last 334 a few days. Conversely, long lasting EPDs result from short daylight duration in winter. This 335 336 effect is logically strengthened in Northern regions (here NO) where it is clearly visible for both moderate and severe EPD. In medium latitude countries, it only impacts moderate droughts 337 whereas no effect can be found in Mediterranean regions. 338

Whatever the energy source, severe droughts are expected to be less numerous and to present lower mean durations than moderate ones. This is roughly the case for all regions. However, solar EPD in Nordic regions do not respect this rule as a result of the bimodal distribution of drought duration mentioned previously. For these regions, when going from moderate to severe droughts, only short duration events are removed whereas long duration ones remain. It then results in an increase of the mean drought duration.

345 4.3 Energy Supply Droughts

As mentioned in Sec.1, low production periods can be more (resp. less) critical when cooccurring with high (resp. low) energy demand. **Fig.6** presents the differences in number of days in drought conditions, mean duration and mean annual frequency of droughts between EPD and ESD.



350

Fig.6: Difference in statistical characteristics from Energy Supply Droughts to Energy production Droughts (ESD-EPD). x-axis: difference in mean duration of drought sequences; y-axis: difference in annual frequency. Colour scale: difference in the number of days in drought state over the simulation period.

For wind power droughts the mean duration of EPD and ESD are very similar whatever the region. The differences in droughts frequencies are also limited for most regions. However, the number of drought days and the annual frequency of drought events tend to be slightly smaller for ESD in Northern regions. It likely results from the partial synchronism between wind 359 power and demand which both present a seasonal pattern with higher values in winter (higher 360 wind speed and higher demand from heating systems). However, the production / demand co-361 variability structure can sometimes lead to opposite changes for moderate and severe droughts 362 (e.g. NO).

The characteristics of solar power droughts are strongly impacted by the energy demand. 363 The number of days in drought situation is higher everywhere, except in the southern regions. 364 This result is consistent with the synchronism existing between low winter production due to 365 short day length and high winter energy consumption in northern and central Europe. It is 366 367 noteworthy that for most regions, higher numbers of drought days are associated with smaller frequencies of drought events (e.g. all regions for moderate droughts and Scandinavian regions 368 for severe droughts). Naturally, this effect is balanced with higher droughts durations. Finally, for 369 some remaining cases (e.g. RO for severe droughts), higher number of drought days result from 370 more droughts sequences but with no changes in mean duration. 371

372 For hydro power, the differences between EPD and ESD are strongly region-dependent. 373 The number of droughts days slightly decreases in regions where hydrological regimes present higher river discharge in winter (e.g. FR, GE, GA, GR). ESD tend to be shorter than EPD. This 374 results from the seasonal co-variability between precipitation and electricity demand with higher 375 precipitation, discharge and hydropower production in winter, when heating systems are 376 operating. The opposite co-variability structure happens for the other regions (continental, 377 378 mountainous and Scandinavian regions) where a higher winter energy demand co-occur with low winter discharges. This latter configuration increases the number of days in drought conditions 379 with shorter and more frequent ESD sequences in NO or longer sequences with similar annual 380 frequency in RO for instance. 381

Whatever the energy source, small differences exist between EPD and ESD in southern regions. It is probably a consequence of a lower sensitivity of the demand to regional temperature changes. Indeed, the weather is relatively mild from autumn to spring, making the demand roughly weather-independent. In other countries, heating systems tend to boost the winter demand. On the other hand, the summer increase in demand from air conditioning is of relatively small magnitude in our temperature-demand model (**Fig.7**).



388

Fig.6: Temperature to energy demand function (dashed broken linear line) with seasonal and annual
 distributions of daily temperature (DJF-blue, MAM-green, JJA-ref, SON-orange, annual-black). See
 Fig.S3 for results on all 12 regions.

394 **5. Discussion**

In Sec.4, we showed that the characteristics of Energy Droughts depend on both energy source and regional climate. They are also expected to depend on non-climatic factors such as technical components and structural choices for power supply systems. In this section we illustrate how Energy Drought's characteristics would be changed for power system using a mix of energy sources or including some storage facilities to balance the production/demand temporal mismatch.

401 **5.1 Energy droughts for an energy mix**

Mixing energy sources is known to reduce the variability of the production and classically improves the production/demand match [11]. For the 12 European regions considered here, François et al. [12] estimated energy mixes based on hydro, solar and wind power, which maximize the mean daily production/demand match (c.f. share coefficients in Tab.1). We here illustrate how this mix may also influence the statistical characteristics of Energy Droughts.

Fig.8 presents the characteristics of EPD obtained with these regional mixes for both 407 moderate and severe droughts. It should be compared to Fig.4 which presents the results of single 408 409 VRE sources. In all cases, a large decrease in drought severity is obtained with the mix. The number of days under drought conditions is drastically decreased, by a factor 2 to 10 depending 410 on the region and on the single VRE source considered initially. This decrease results in a large 411 reduction of both duration and frequency of energy droughts. For some regions, the combination 412 of VRE sources even leads to the complete removal of severe droughts (e.g. AN). Thus, the 413 414 complementarity that exists between VRE sources can make power systems much less prone to EPD. 415



416

Fig.7: Effect of a VRE mix (see Tab.1) on moderate and severe Energy Production Droughts. Figure
to be compared with Fig.4 (caption details in Fig.4).

419 **Tab.1: Regional energy mix proposed by François et al.** [12]. Share coefficients are given for solar 420 power (S_{PV}), wind power (S_w) and hydropower (S_{RoR}) for the 12 regions.

	S _{PV} (%)	S _W (%)	S _{RoR} (%)
Finland	15	35	50
Norway	15	50	35
Belarus	5	30	65
England	20	15	65
Germany	35	15	50
France	45	15	40
Italy	30	35	35
Romania	25	35	40
Greece	45	10	45
Galicia	45	10	45
Andalucía	50	10	40
Tunisia	40	20	40

421 **5.2 Energy droughts and storage**

422 Storage systems, such as water reservoirs and batteries, can also ease the integration of 423 VRE; balancing part of the missing production with the energy surplus stored on previous days 424 [44][45][46].

Fig.9 presents the effect of storage on ESD characteristics in NO, GE and AN. Similar results are obtained for the other regions. We consider 4 simplified and idealized storage systems with different storage capacities corresponding respectively to 1, 7, 30 and 90 days of mean energy load. The energy transfer from and toward the storage system is simulated on a daily basis. Depending on the daily production/demand balance, the storage system either fills up, storing the energy surplus, or runs out, to satisfy more demand (see [47] for details). For simplification, we assume a perfect storage (no power loss).

For wind power, the frequency of drought episodes is efficiently lowered even with small storage capacity. When a large storage is involved, only few drought events remain. This result directly comes from the high frequency variations of wind power and the short durations of wind power droughts.

As mentioned previously, hydro power droughts have rather long duration in most
regions. Therefore, small size storage systems do not lead to a significant reduction of droughts:
the number of drought days does not change much. However, small size storage leads to a

reduction of droughts frequency, which is counterbalanced with an increase in mean drought duration. A significant reduction of drought severity is obtained for storage capacities larger than 30 days of mean demand. The seasonal based size (S = 90) is even more efficient but still does not lead to similar improvement as for wind power.

443 Similar comments apply for solar power. Small storage capacity does not change the 444 number of drought days but often leads to longer and less numerous droughts events. Different 445 modifications occur depending on the regional location in latitude. Even with large storage 446 systems, Northern regions still suffer from long and numerous solar power droughts. Conversely, 447 these critical periods are almost all removed in Mediterranean regions, even with medium storage 448 capacity (here AN).



⁴⁴⁹ 450

Fig.8: Effect of storage on Energy Supply Droughts characteristics. Mean number of drought episodes versus mean drought duration. Results are displayed for hydro-power (blue), solar-power (red), windpower (orange). The points associated to different storage capacities but from the same energy source have been connected in a logical order. They correspond to S = 1, 7, 30 and 90 days of mean energy load (S=1 in bold). The colour scale gives the mean annual number of days under drought conditions. See Fig.S4.a and Fig.S4.b for results on all 12 regions.

457 **6.** Conclusions

The similarities in stochastic nature and characteristics (occurrence, duration, intensity) between low production periods from VRE sources and low flow periods in hydrology call for the introduction of the concept of Energy Droughts.

In this study, we showed the strong variations of Energy Droughts characteristics between 461 sources and within Europe. Wind droughts are very numerous but present very short duration, 462 whatever the location. Solar droughts are of two types: 1) those that directly derive from the 463 seasonal cycle of daylight which are long lasting especially in northern regions 2) those induced 464 by the weather variability (changes in cloud cover) which usually last a few days maximum. 465 Hydropower droughts are much more region and time dependent as a result of the combined 466 effects of meteorological droughts (snow accumulation or lack of rainfall / snow melt) and of the 467 low pass filtering behaviour of river basins. Whatever the region, the complementarity that exists 468 between wind, solar and hydro would make VRE mixes much less prone to energy droughts than 469 systems based on one single VRE source. 470

The characterization of Energy Droughts is expected to enlighten decision makers in the design of future renewable power systems, including the provision of backup and/or storage solutions. As illustrated in this study, the analysis of Energy Droughts should take into account the electricity demand sensitivity to weather conditions. Indeed, it can potentially increase / decrease the socio-economic impact of drought events, depending on the co-variability structure between production and demand.

Our work is based on a number of assumptions, data and modelling choices, which 477 potentially lead to some uncertainty in our results. The hydro-meteorological data used here are 478 not observations but pseudo-observations (e.g. radiation from satellite products, surface winds 479 from WRF). Of course, such data present limitations. However, conversely to observed data, 480 pseudo-observations are available at high space - time resolution and classically cover rather long 481 periods of time, even in ungauged regions. They allow having a more relevant view of unusual 482 hydro-meteorological events. The temporal and spatial organisation (and next co-variations) of 483 these pseudo-observations is also a priori consistent with the weather conditions of the 1983-2012 484 period. Thus, our analysis is expected to give a reasonable picture of the main features of energy 485 droughts in different European climates for the last decades and of their specificities for the 486 different types of VRE sources. However, further studies should consider the possibility to use 487 the higher quality datasets (e.g. high resolution reanalyses of surface weather) that should be 488 available in the coming years. 489

The choice of the weather-to-energy model is also another source of concern. Generic 490 production systems have been considered for all regions. However, a variety of technological 491 solutions which have their own weather-to-energy conversion relationships exist to harvest 492 VREs. These relationships are classically highly non-linear and vary from one plant to the other. 493 For instance, this is the case for wind turbines (cut-in / cut-off thresholds in the wind speed – 494 wind power relationship) or for hydropower-plants which present an even greater variety with 495 site-dependent specificities. Consequently our results are expected to significantly depend on 496 these technical features. Similarly, the weather driven part of the energy demand was estimated 497 498 with a unique model for all regions. However, the sensitivity of the demand to temperature can strongly vary from one region to the other. For instance, the winter sensitivity in FR and NO is 499 actually twice higher than the average relationship estimated for our 12 European regions; most 500 heating systems being based on electricity in these regions. Similarly, the summer sensitivity is 501 roughly 5 times greater in IT and GR than elsewhere as a result of a much higher proportion of 502 503 households equipped with air conditioning. The weather sensitivity of the demand obviously determines the differences between Energy Production Droughts and Energy Supply Droughts. 504 Further studies should explore how our results depend on the technical and socio-economic 505

506 configuration. However, the main conclusions of our analysis are not expected to drastically 507 change.

As mentioned previously, Energy Production Droughts are a signature of weather and 508 509 hydrometeorological variability. Thus, they are defined per-se. Conversely, Energy Supply Droughts depend on a number of socio-economic and technical factors, including those 510 pertaining to the energy mix and the power system considered. To provide some insight on 511 Energy Supply Droughts, part of our analysis was carried out with the 100% renewable energy 512 scenario. In this context, we assume that the resource is sufficient to provide the whole energy demand. 513 This is likely not the case for all the configurations we considered. This would depend on the available 514 515 mean resource itself which can be rather low in some regions (e.g. solar in the north) and on the mean demand which can be rather large in highly populated areas. The operational feasibility of such a 516 100% scenario is also obviously questionable, as discussed in a number of recent publications 517 (see for instance [48] and [49]). Whatever those possible limitations, the 100% VRE scenario offers 518 a convenient and simple analysis framework able to give informative perspective of a 519 configuration to which a number of countries / regions are prone to head toward [1]. In our 520 analysis, it allows highlighting the interest of mixing of solar/hydro/wind sources, using the 521 522 space/time complementarity between single sources. It also allows analysing how low resources 523 sequences could interplay with high demand sequences as a result of the co-variability between weather variables. The analysis proposed here thus allows drawing a first but already informative 524 picture of other energy droughts issues. Further works should consider a more realistic 525 representation of the energy mix and power system. We here for instance focused our analysis on 526 527 specific European regions assumed to be independent from each other. This is obviously not the case owing to the wide European electricity grid which connects regions and makes them less 528 529 vulnerable to local weather variations. Further works should then consider Energy Droughts in a broader space-time framework to determine the characteristics of Energy Droughts over a 530 continuum of spatial scales from local to European ones. The potential severity of European-wide 531 events is of major interest for building a reliable pan-European power system. On the other hand, 532 Energy droughts should also be studied at a very local scale, for a reliability analysis of mini-533 534 grids and stand-alone power systems which are appropriate for remote and isolated communities and/or industries. 535

Energy Droughts are a key security issue of the energy supply challenge in a context 536 where the share of VRE is continuously increasing worldwide. This call for a detailed 537 538 characterization of their main statistical properties and extreme return levels similarly to what is classically done for meteorological and/or hydrological extremes. This characterization should 539 account for the likely intensification of the hydrological cycle and of hydro-meteorological 540 extremes expected from the ongoing climate change. Energy droughts will likely also challenge 541 the operational management of the energy systems. To support their real-time management for 542 instance, further works should also explore / understand the large-scale meteorological and/or 543 atmospheric configurations prone to Energy Droughts and assess the possibility to forecast such 544 545 events. We can likely expect that these different issues will gain increasing attention in the coming years. 546

547

548 **7. Acknowledgement**

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This work is part of the FP7 project COMPLEX (Knowledge based climate mitigation systems
for a low carbon economy; Project FP7- ENV-2012 number: 308601;
http://www.complex.ac.uk/).

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554 8. References

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