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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-02327441>

Submitted on 26 Nov 2020

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Energy droughts from variable renewable energy sources in European climates

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Manuscript accepted for publication in Renewable Energy

Citation : Raynaud, D., Hingray, B., François, B., Creutin, J.D. 2018. Energy droughts from variable renewable sources in European climates. Renewable Energy. 125: 578-589,

<https://doi.org/10.1016/j.renene.2018.02.130>

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.

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 demand. The characteristics of EPD are very different between sources with short but frequent wind power droughts and rare but long hydro power ones. Solar power droughts are very region-dependent with much longer droughts in Northern Europe. ESD are next characterized in a 100% renewable energy scenario. The features of EPD and ESD differ significantly, highlighting the interplay with the energy demand. Moreover, both duration and frequency of energy droughts decrease when mixing energy sources or when some storage capacity balances the temporal production / demand mismatch.

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

38 1. Introduction

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

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

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

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

77 Low VRE production conditions can be also problematic. They result from weather or
78 hydrometeorological configurations with low VRE resources or from situations for which a
79 production curtailment is necessary to avoid damage on power production units (e.g. when wind
80 speed exceeds the cut-off threshold of wind turbines). They can induce critical situations in term
81 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.

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

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].

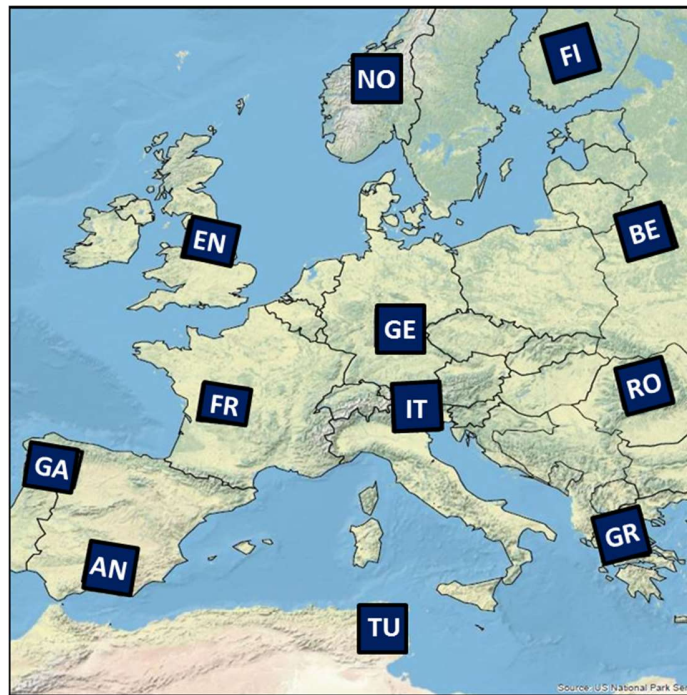
100
101 In this study, we propose to complement and enlarge these analyses by characterizing and
102 comparing the periods of low VRE production in Europe for the three main renewable power
103 sources, namely wind, solar and hydro power from river flows. We consider the three sources
104 separately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

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**

123 We consider twelve regions homogeneously spread over Europe and Maghreb and having
124 a surface area of about 40000km² (**Fig.1**). As discussed in François et al. [12], they draw a picture
125 of the large variety of climatic conditions existing in Europe with four main influences: a North-
126 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
131 demand time series. Temperature and precipitation data are based on on-site measurements and
132 are extracted from the European Climate Assessment & Dataset (ECAD, [37]) at a daily time step
133 and on 0.25 degrees grid spacing. Solar radiation series comes from the Surface Solar Radiation
134 Dataset - Heliosat (SARAH) which relies on satellite measurement [38]. It has a 0.05° grid and
135 data are also extracted on a daily basis. Finally, we use pseudo-observations of wind speed
136 derived from simulations of the Weather Research and Forecasting Model which has been forced
137 by the ERA-Interim reanalysis [39]. All these data are available on a 30-yr long research period,
138 extending from 1983 to 2012.

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

146 2.2 Weather-to-energy conversion models

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

153 For each grid, solar power (P_{PV}) time series is derived from global solar irradiance I_{eff}
154 (Wm^{-2}) and air temperature T_a ($^{\circ}C$) following Perpiñan et al. [41]. The conversion of wind speed
155 into wind power relies on a two-step process. Firstly, the 10m wind speed series are extrapolated
156 to 80m (height of the generic turbine hub), assuming a logarithmic increase in wind speed with
157 increase in altitude. Daily wind speed is then converted into wind power with the idealized power
158 curve described in Francois et al. [12]. To estimate RoR hydro power from river discharge P_{RoR}
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.

$$P_{RoR}(t) = \eta_H g h \rho q(t) \quad (1)$$

161 where η_H the efficiency of the turbine (%), q the flow passing through the turbine
162 ($m^3 \cdot s^{-1}$), g the acceleration of gravity ($=9.81 m \cdot s^{-2}$), ρ the water density ($=1000 kg \cdot m^{-3}$). 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:

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

171 where T_{Heat} and T_{Cool} are the heating and cooling thresholds ($15^{\circ}C$ and $20^{\circ}C$ respectively),
172 b (Wh) is the base load for the temperature-independent range and a_{Theat} ($Wh \cdot ^{\circ}C^{-1}$), a_{TCool} ($Wh \cdot ^{\circ}C^{-1}$)
173 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, <https://www.entsoe.eu/home/>) (more
176 details in François et al. [12]).

177 3. Definition of energy droughts

178 3.1 Energy Production Droughts (EPD)

179 We define a low production period as a contiguous sequence of days during every day of
180 which the production is below a given low-production threshold. This analysis requires the
181 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**).

$$184 \quad DI(j) = 1 \text{ if } P(j) \leq P_0 \quad (3)$$

$$185 \quad DI(j) = 0 \text{ if } P(j) > P_0$$

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

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

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

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

203 3.2 Energy Supply Droughts (ESD)

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

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

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

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

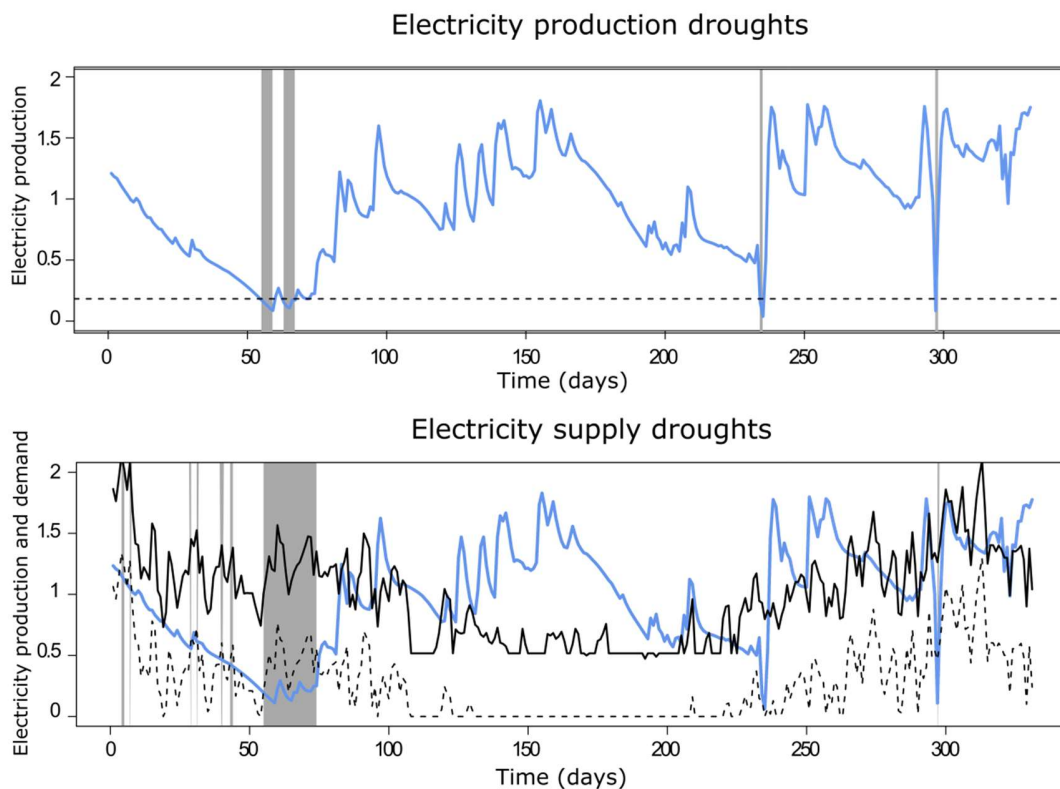
$$222 \quad SDI(j) = 0 \text{ if otherwise} \quad (4)$$

223 Where $D(j)$ is the energy demand on day j , D_m is the mean daily energy demand over the
 224 whole 1983-2012 period. The main characteristics of low satisfaction periods are derived from
 225 the time series of the SDI index similarly to what has been described for Low Production Periods
 226 in Section 3.1 (see **Fig.2b**). We consider two thresholds values, $k=0.5$ and $k=0.8$, which
 227 correspond to what we will call moderate and severe Energy Supply Droughts respectively (ESD
 228 in the following).

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

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

238



239

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

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

248 4. Results

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

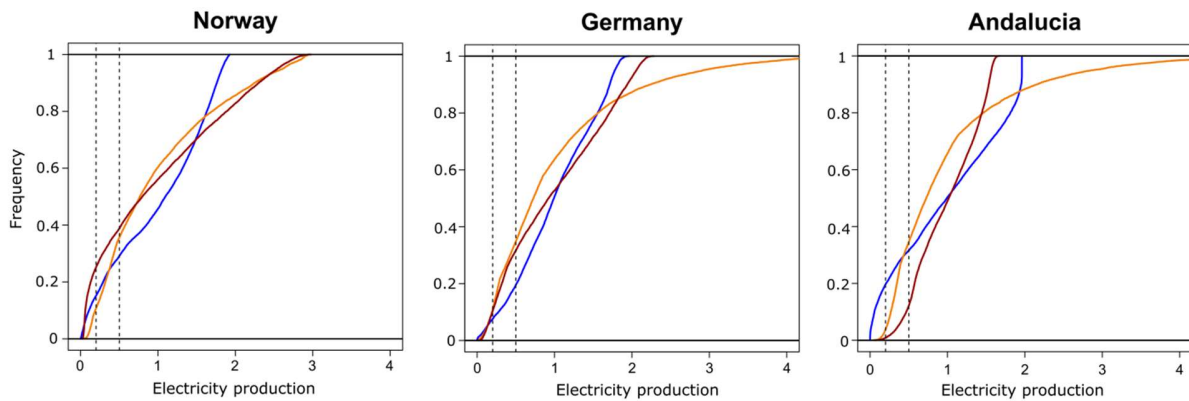
253 4.1 Days in drought state

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

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

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

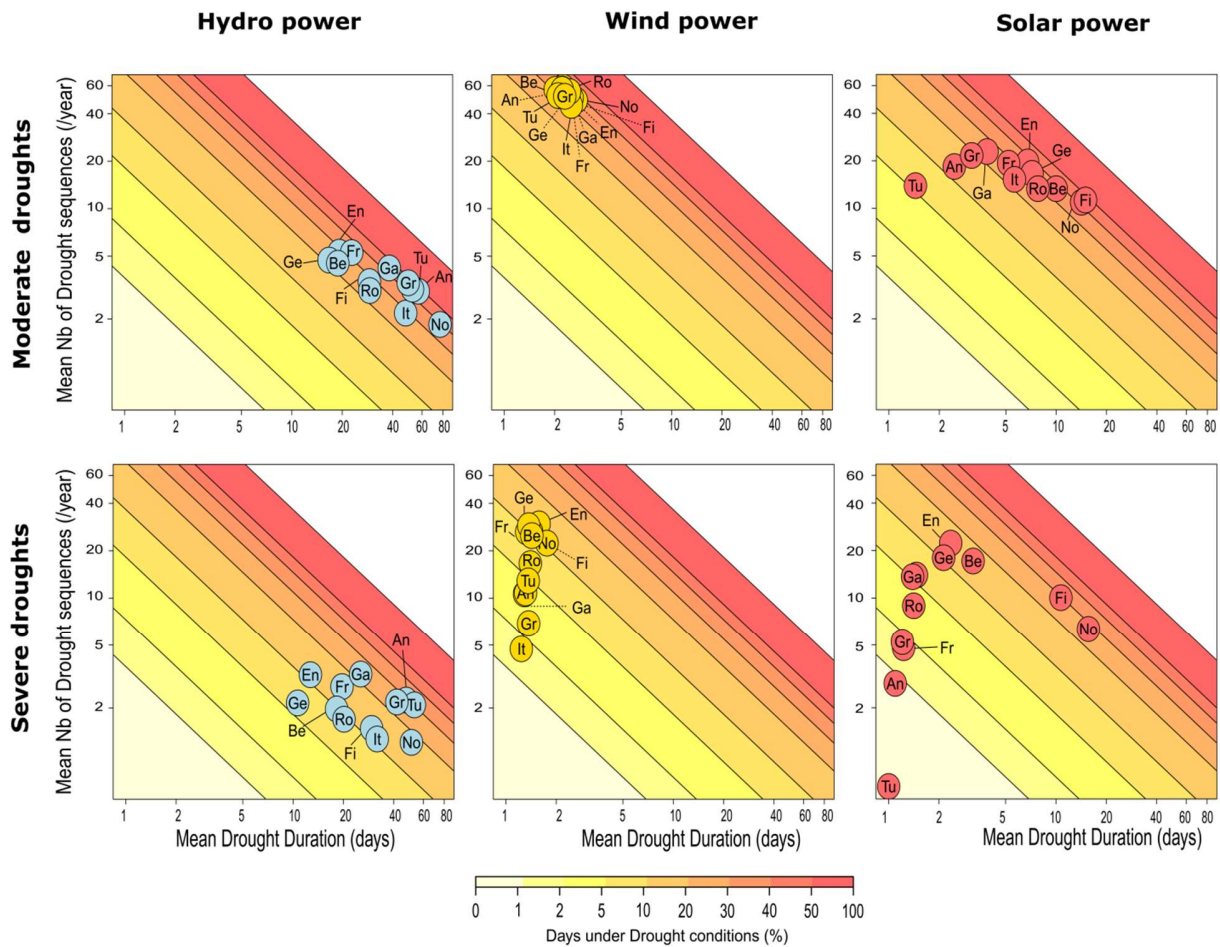
269 For hydropower, the cdf of daily production can have very different shapes from one
270 region to the other. They have similar shapes in Alpine areas, Northern and southern European
271 regions (here NO and AN) with a large proportion of days below the drought thresholds (15%
272 below the 0.2 threshold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



277
 278 **Fig.3: Cumulative distribution functions (cdfs) of normalized power production for each VRE**
 279 **source in 3 European regions. Hydro – blue, Wind – orange, Solar – red. See Fig.S1 for results on all 12**
 280 **regions**

281 **4.2 Energy Production Droughts**

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

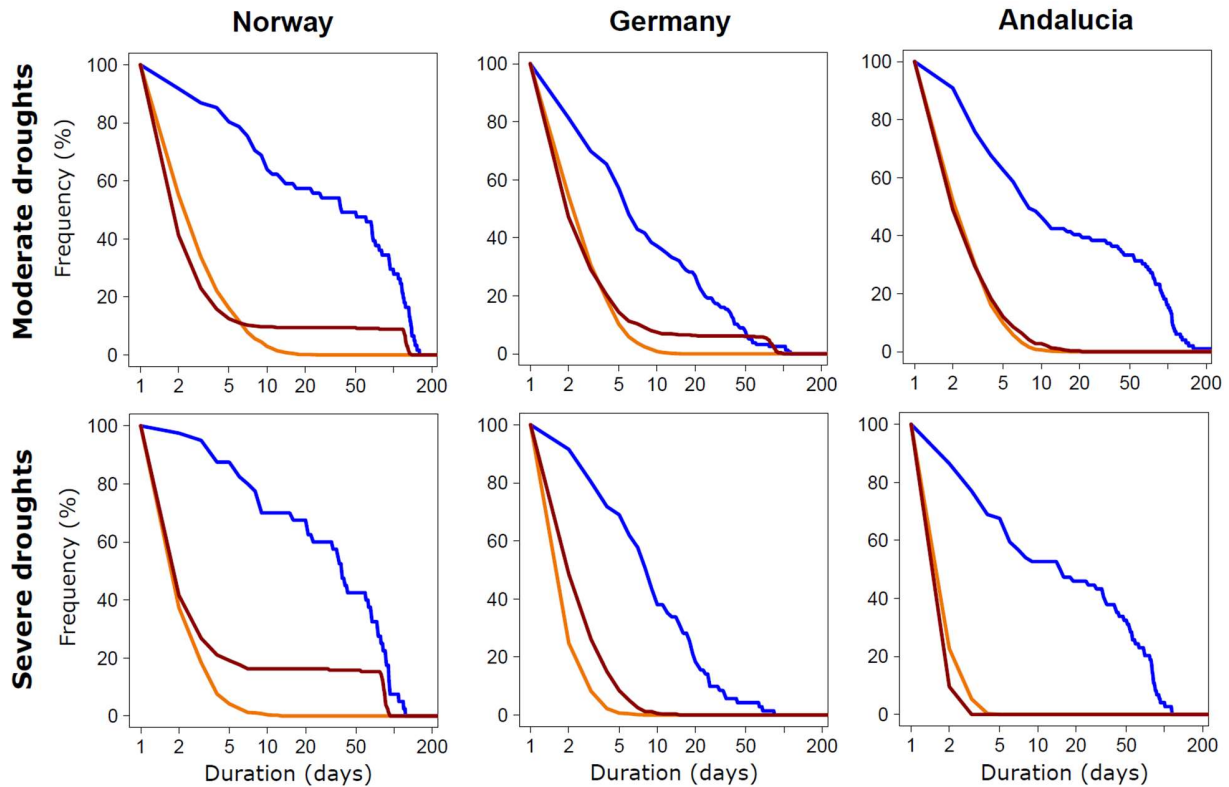


290

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

296

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



302

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

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

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

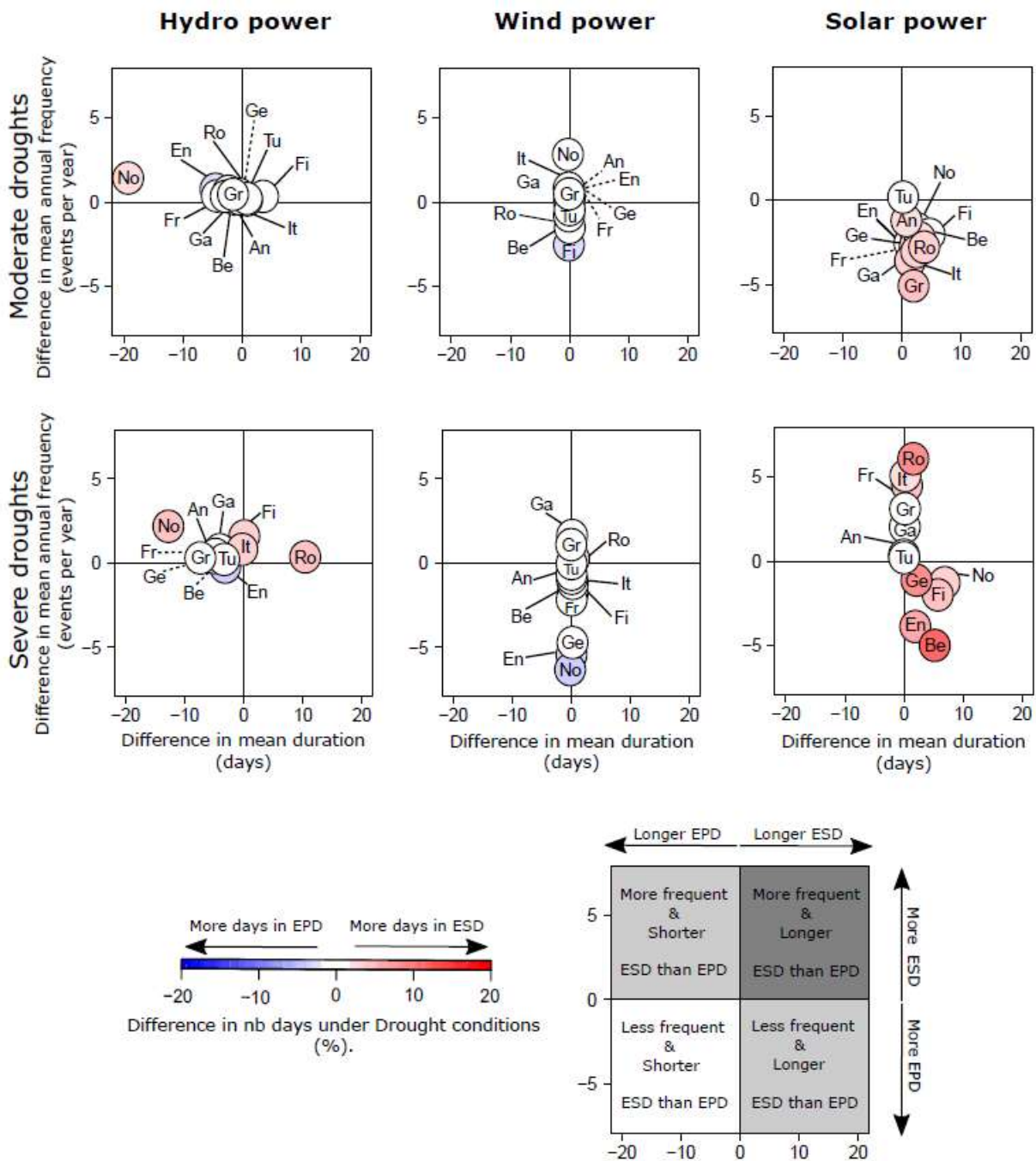
326 elevation/latitude regions, from the storage in snowpack of most winter precipitation. Finally, the
327 characteristics of hydropower droughts also significantly depend on the drought intensity level.
328 Severe hydropower EPD are roughly twice less numerous than moderate ones. They also last
329 30% to 50% time less. The regional specificities are roughly the same for both drought intensity
330 levels.

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

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

345 **4.3 Energy Supply Droughts**

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



350

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

355 For wind power droughts the mean duration of EPD and ESD are very similar whatever
 356 the region. The differences in droughts frequencies are also limited for most regions. However,
 357 the number of drought days and the annual frequency of drought events tend to be slightly
 358 smaller for ESD in Northern regions. It likely results from the partial synchronism between wind

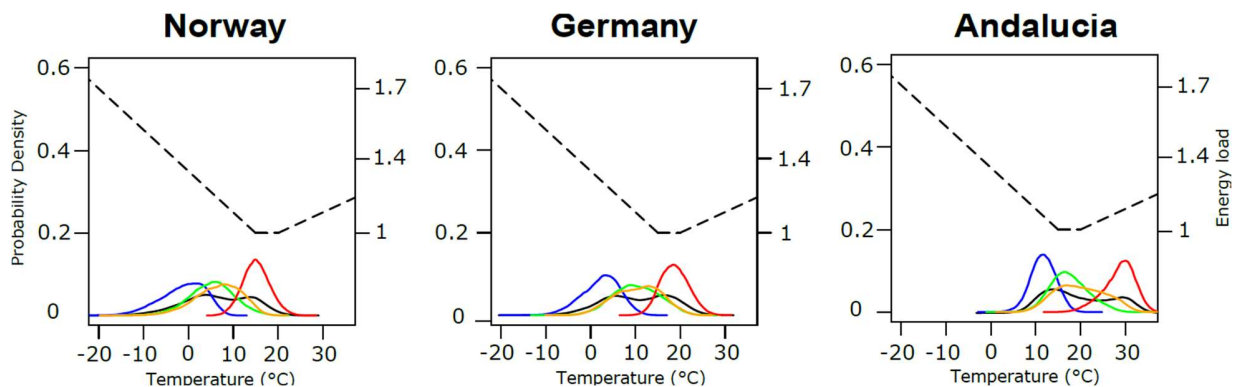
359 power and demand which both present a seasonal pattern with higher values in winter (higher
360 wind speed and higher demand from heating systems). However, the production / demand co-
361 variability structure can sometimes lead to opposite changes for moderate and severe droughts
362 (e.g. NO).

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

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

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

388



389

390

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

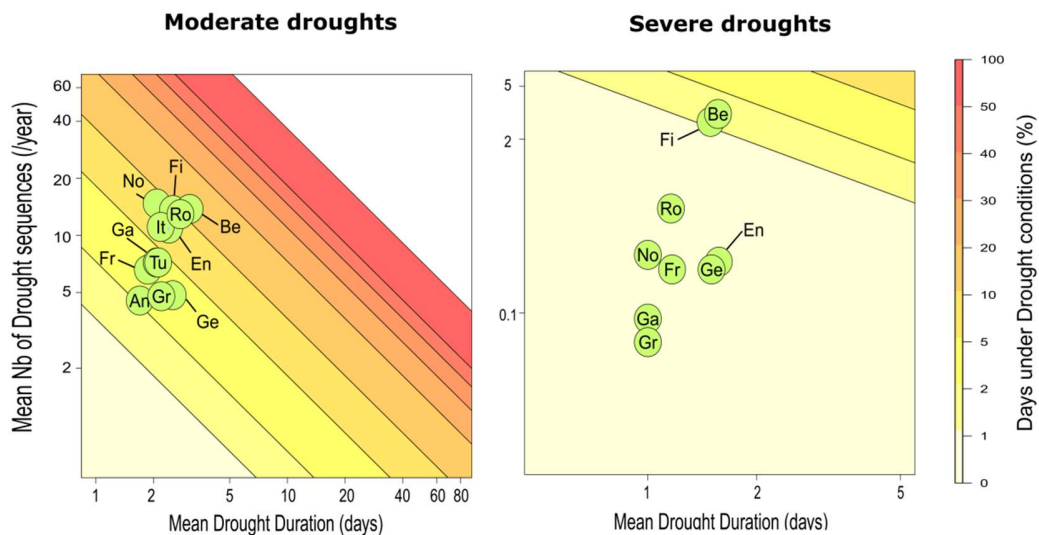
394 5. Discussion

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

401 5.1 Energy droughts for an energy mix

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

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



416
 417 **Fig.7: Effect of a VRE mix** (see **Tab.1**) **on moderate and severe Energy Production Droughts.** Figure
 418 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].

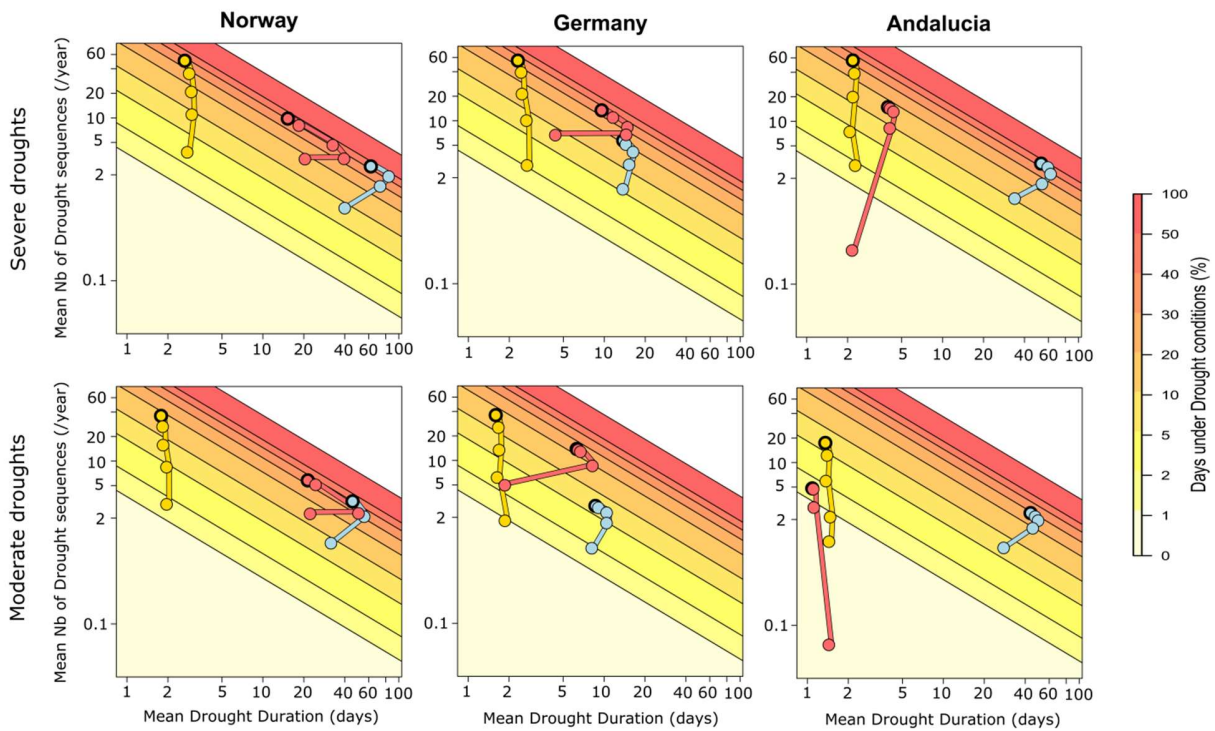
425 **Fig.9** presents the effect of storage on ESD characteristics in NO, GE and AN. Similar
 426 results are obtained for the other regions. We consider 4 simplified and idealized storage systems
 427 with different storage capacities corresponding respectively to 1, 7, 30 and 90 days of mean
 428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

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

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

439 reduction of droughts frequency, which is counterbalanced with an increase in mean drought
 440 duration. A significant reduction of drought severity is obtained for storage capacities larger than
 441 30 days of mean demand. The seasonal based size ($S = 90$) is even more efficient but still does
 442 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
 451 **Fig.8: Effect of storage on Energy Supply Droughts characteristics.** Mean number of drought episodes
 452 versus mean drought duration. Results are displayed for hydro-power (blue), solar-power (red), wind-
 453 power (orange). The points associated to different storage capacities but from the same energy source
 454 have been connected in a logical order. They correspond to $S = 1, 7, 30$ and 90 days of mean energy load
 455 ($S=1$ in bold). The colour scale gives the mean annual number of days under drought conditions. See
 456 Fig.S4.a and Fig.S4.b for results on all 12 regions.

457 6. Conclusions

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

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

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

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

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

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

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

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

547

548 **7. Acknowledgement**

549
550 This work is part of the FP7 project COMPLEX (Knowledge based climate mitigation systems
551 for a low carbon economy; Project FP7- ENV-2012 number: 308601;
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