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How Does Climate Change Affect The Transition Of Power Systems *Already Now*: The Case of Germany

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Content

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Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

1. Motivation
2. Data
3. Experiment setting and preliminary results
4. Conclusions and takeaway

Interrelation of climate change and the power system

- Energy sector is the largest contributor to greenhouse gases in the EU [Eurostat, 2017].
- Climate change policies aim towards the transition of energy sector towards a low carbon system.
- Energy system itself is affected by climatic changes:
    - Availability of renewable energy sources (RES).
    - Availability of cooling water for thermal power plants: Effects of changes in climatic conditions on thermal power plants reduce electricity generation efficiency (heat waves) and supply reliability (water scarcity).

EU regulatory framework

- Water Framework Directive [Directive 2000/60/EC].
- European Freshwater Fish Directive [Directive 2006/44/EC].
- Energy Union strategy: EU demands from member states information on national adaptation actions, in particular on availability of cooling water for power plants (paragraph 44) [Regulation (EU) 2018/1999].
- European Programme for Critical Infrastructure (EPCIP) [SWD(2013) 318]:
  - energy and transport sectors are gathered under the name “European critical infrastructures” (ECI) [Directive 2008/114/EC].

Motivation: Background Literature

	energy		transport	
heat	***reduced power output***:		***direct damages to infrastructure***:	
	- decrease in efficiency due to high ambient temperature	Cortekar & Groth [2015] Hoffmann et al. [2013]	- road ways: material fatigue due to thermal expansion	Altvater et al. [2012]
	- decrease in efficiency due to water cooling system failures in thermal power plants (nuclear and fossil)	Van Vliet et al. [2016] Van Vliet et al. [2012]	- electricity transmission and distribution grids: due to efficiency losses	Cortekar & Groth [2015] Altvater et al. [2012]
	- decrease in PV efficiency due to high ambient temperature	Altvater et al. [2012]	- gas transmission grids	Altvater et al. [2012]
	high electricity demand for cooling (households, food industry)	Altvater et al. [2012]		
drought	***reduced power output***:		***strained navigation of river ways***:	
	- hydropower	Van Vliet et al. [2016] Rübbelke & Vögele [2013] Van Vliet et al. [2013]	- delivery of goods: restriction of loading capacity	Altvater et al. [2012]
	- CCS (water intake and discharge for cooling)	Byers et al. [2016]	- delivery of fuel (e.g. bulk ships for coal delivery)	Altvater et al. [2012]
	- biofuel production			
	- nuclear power plants (regulation on water intake for cooling)	Förster H, Lilliestam [2010] Van Vliet et al. [2016] Rübbelke & Vögele [2011] Ecofys [2014]		
	- thermal power plants esp. gas and hard coal (regulation on water intake for cooling)	Hoffmann et al. [2013] Altvater et al. [2012] Van Vliet et al. [2012] Byers et al. [2016]		

Motivation: Background Literature

energy

reduced power output:

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Climate data is based on historical period **1971–2000**.

Future periods: **2031–2060**.

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- thermal power plants esp. gas and hard coal (regulation on water intake for cooling) — Hoffmann et al. [2013], Altvater et al. [2012], **Van Vliet et al. [2012]**, Byers et al. [2016]

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- road ways: material fatigue due to thermal expansion — Altvater et al. [2012]
- electricity transmission and distribution grids: due to efficiency losses — Cortekar & Groth [2015], Altvater et al. [2012]
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Climate data is based on historical period **1960-1990**.

Future periods: 2011-2040 and **2041-2070**.

st…

- … — …ater et al. [2012]
- delivery of fuel (e.g. bulk ships for coal delivery) — Altvater et al. [2012]

Motivation: Background Literature

	energy		...ort	
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Study is focused primarily on nuclear and hydro power plants.

With coal and gas that can be used "…to fill supply gaps".

Climate data is based on historical period 1971–2000.

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Climate data is based on historical period 1960-1990.

Future periods: 2011-2040 and 2041-2070.

Motivation


Search Bloomberg Sign In

EDF Is Preparing Its Nuclear Reactors for Climate Change

By Francois De Beaupuy

10. Juli 2019, 14:19 MESZ

- Utility is adding more resilient equipment, climate experts
- Move is response to pressure from French safety authority

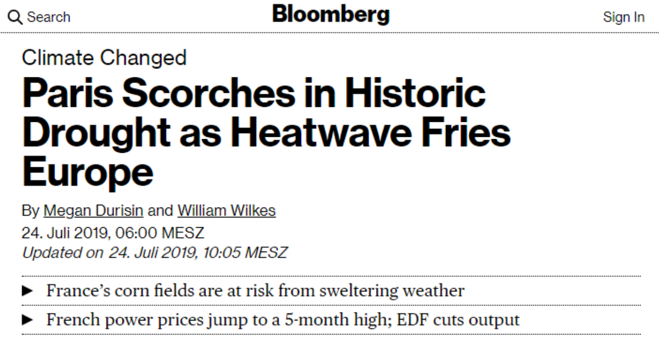

Search Bloomberg Sign In

Europe's Most Important River Risks a Repeat of Historic Shutdown

Looming heatwave raises fears that last year's halt to Rhine shipping could happen again.

By William Wilkes, Bill Lehane, and Vanessa Dezem

23. Juli 2019, 06:00 MESZ


Search Bloomberg Sign In

Climate Changed

Paris Scorches in Historic Drought as Heatwave Fries Europe

By Megan Durisin and William Wilkes

24. Juli 2019, 06:00 MESZ

Updated on 24. Juli 2019, 10:05 MESZ

- France's corn fields are at risk from sweltering weather
- French power prices jump to a 5-month high; EDF cuts output

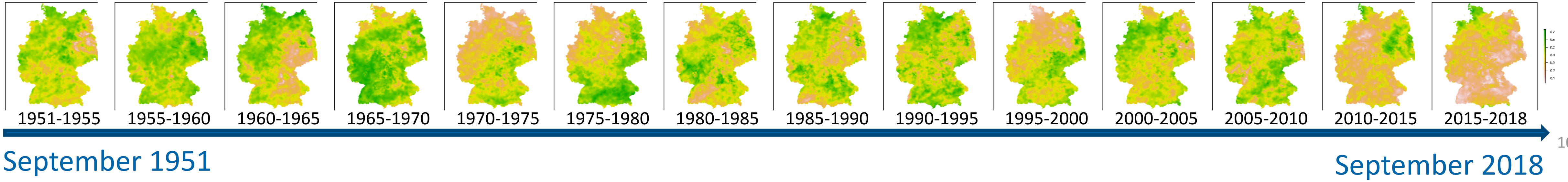
Interrelation of climate change and the power system

- Severe drought during the summer of 2018 resulted in forced shutdowns of thermal power plants in Germany.
- European nuclear power plants faced *cooling problems* due to insufficient water availability in the past [Rübbelke & Vögele, 2011].
- Vulnerability of US and European electricity sector with regard to droughts has been analyzed by Van Vliet et al. [2012, 2016].
- However, their assessments rely on **highly aggregated** power plant data sets.
- The proposed assessment includes data sets with a **high** spatial, temporal, and regional granularity.
  - ➢ Research Question: How do climatic changes affect the stability of the German power system in the short-term?

Data

data	source	time horizon (resolution)
Soil moisture index (SMI) (ncdf)	German Drought Monitor (UFZ Leipzig)	1951-2018 (monthly)
Spatial temperature data (text)	Climate Data Center (Deutscher Wetterdienst)	1983-2018 (daily)
Control area balances (tertiary control reserve) (text)	German TSOs‘ control area balances (50Hz, Ampiron, Tennet, TransnetBW)	2012-2018 (15 min)
Power plant outages (per prod. unit) (xml)	ENTSOe Transparency data	2015-2018 (daily)

- SMI is a quantile-based soil moisture index, based on a 60 year historic soil moisture reconstruction (1954 – 2013).
- The SMI is bounded between 0 and 1. It is estimated on every grid cell and for the particular time of the year (i.e., the average of the 30 days preceding the estimation day).
- The grid cell dimension is roughly equal to 4x4 km.



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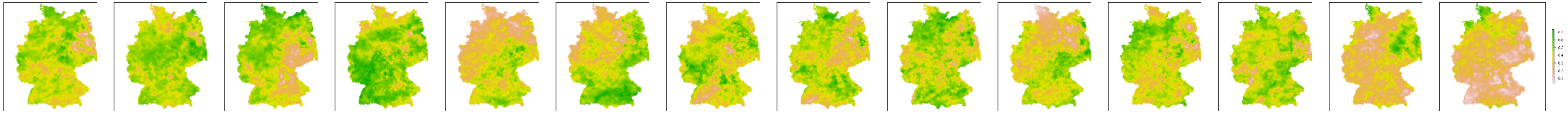
- ***Long-term*** soil water deficiencies (agricultural droughts) diminish to surface and subsurface water availability, resulting in ***hydrological drought***.
- ***Hydrological droughts*** are denoted by reduced stream flow and low water levels of reservoirs and lakes. Hydrological droughts mainly affect water resources management, ***power plant cooling***, irrigation and inland navigation.

[Zink et al., 2016]



1951-1955 1955-1960 1960-1965 1965-1970 1970-1975 1975-1980 1980-1985 1985-1990 1990-1995 1995-2000 2000-2005 2005-2010 2010-2015 2015-2018

September 1951 September 2018

Data

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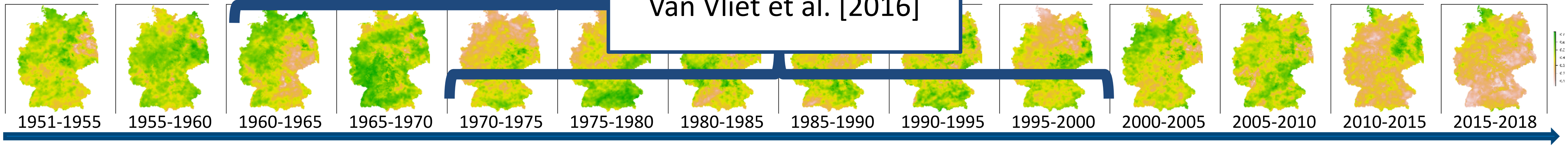
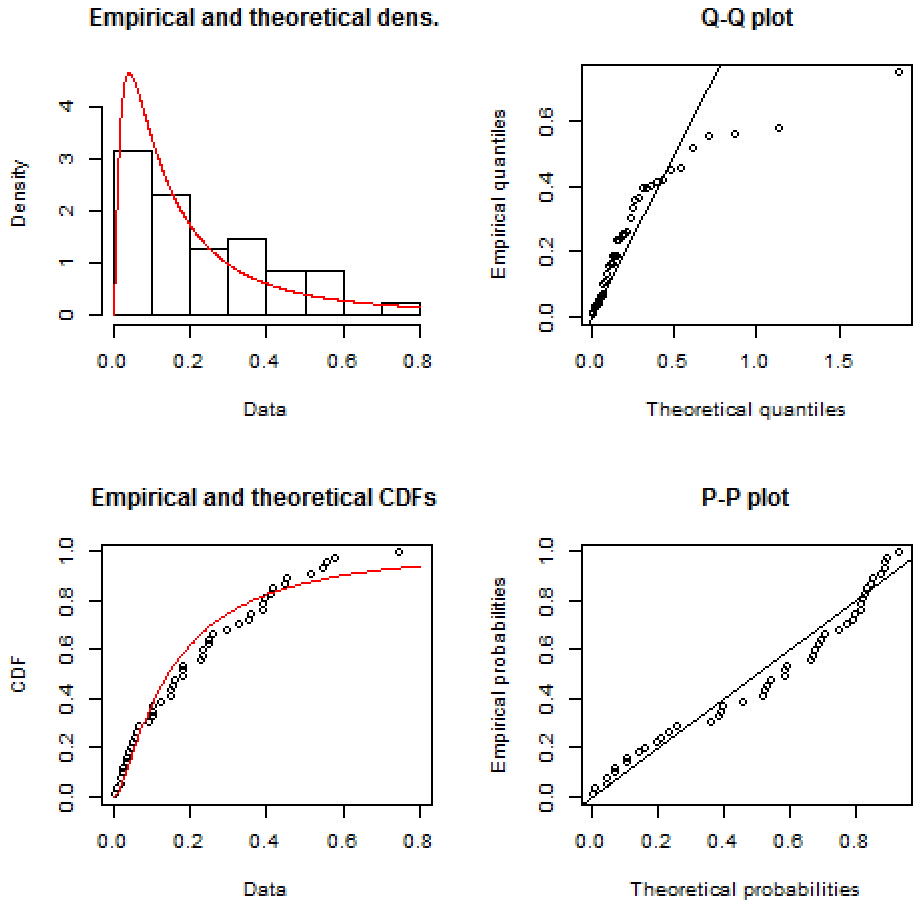


September 1951

September 2018

Prior to estimating probabilities: Log-normal distribution

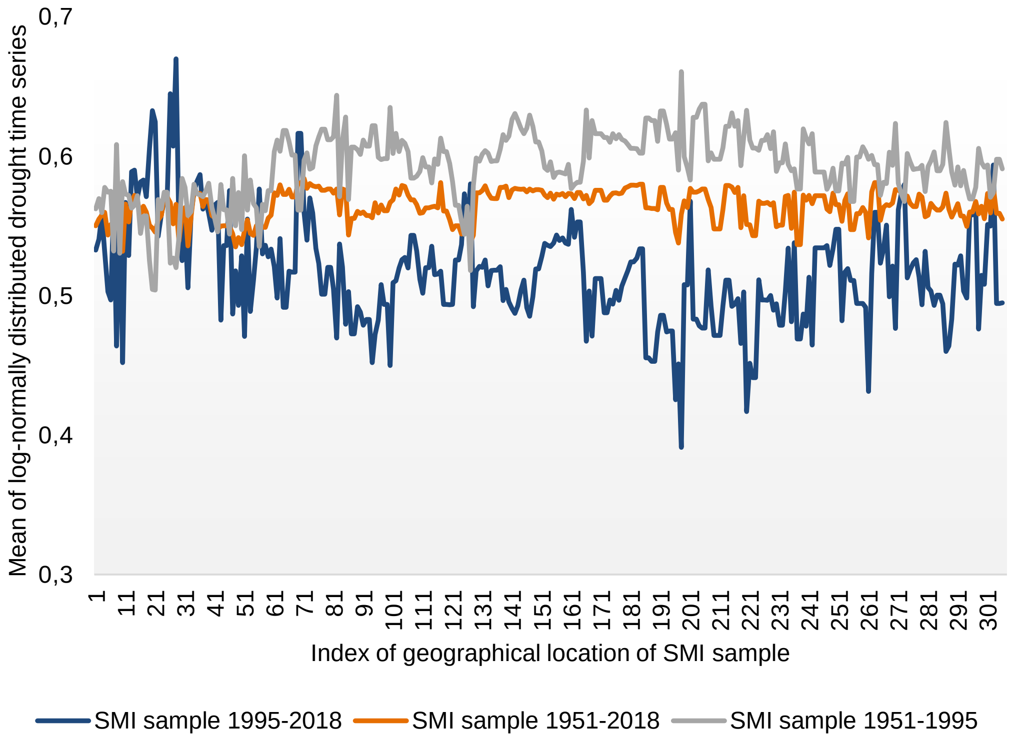
- Normal distribution assumes random variation of independent variables, which effect is **additive** (coin flips).
- Log-normal distribution also assumes random variation of independent variables, but their effect is **multiplicative** (such as measures of air quality, concentration of elements in the earth crust) [see Limpret et al. 2001].
- Positively skewed distributions with kurtosis values > 3, implying on longer “tails” of the probability density functions.

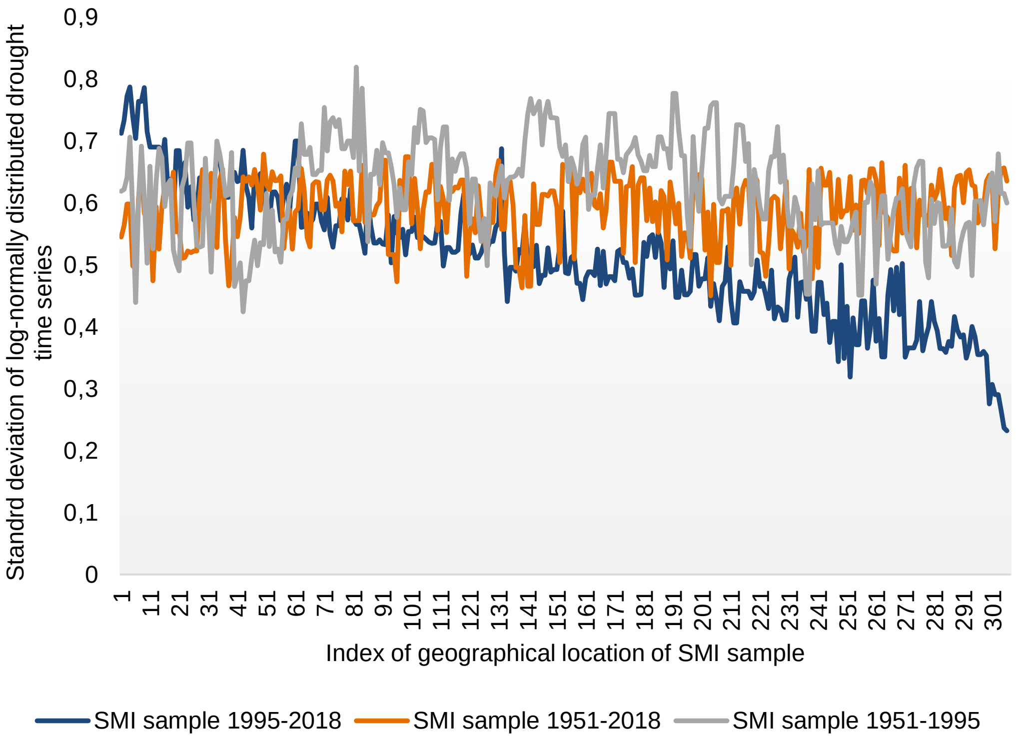


SMI time series fitness test to log-normal (2015-2018)

Gas Power Plant
76189, Karlsruhe, Baden-Württemberg
EIC:11WD4DAXLA-S---6
Lat: 49.00383995 **Lon**: 8.325223707

Prior to estimating probabilities: Log-normal distribution





Recent period from 1995 to 2018 considerably changes the distribution of mean SMI indexes for all geographic locations. It contributes to the conclusion that droughts become more severe.

The volatility of SMI index for each location shows a trend towards dryer weather conditions in most parts of Germany, and increasing risk of severe droughts for particular regions.

Temperatures and Droughts: Cointegration Test (Johansen)

Both data sets cover monthly temperature values and drought index from 01.01.1951 till 31.12.2018 in a monthly resolution – i.e. monthly mean values.

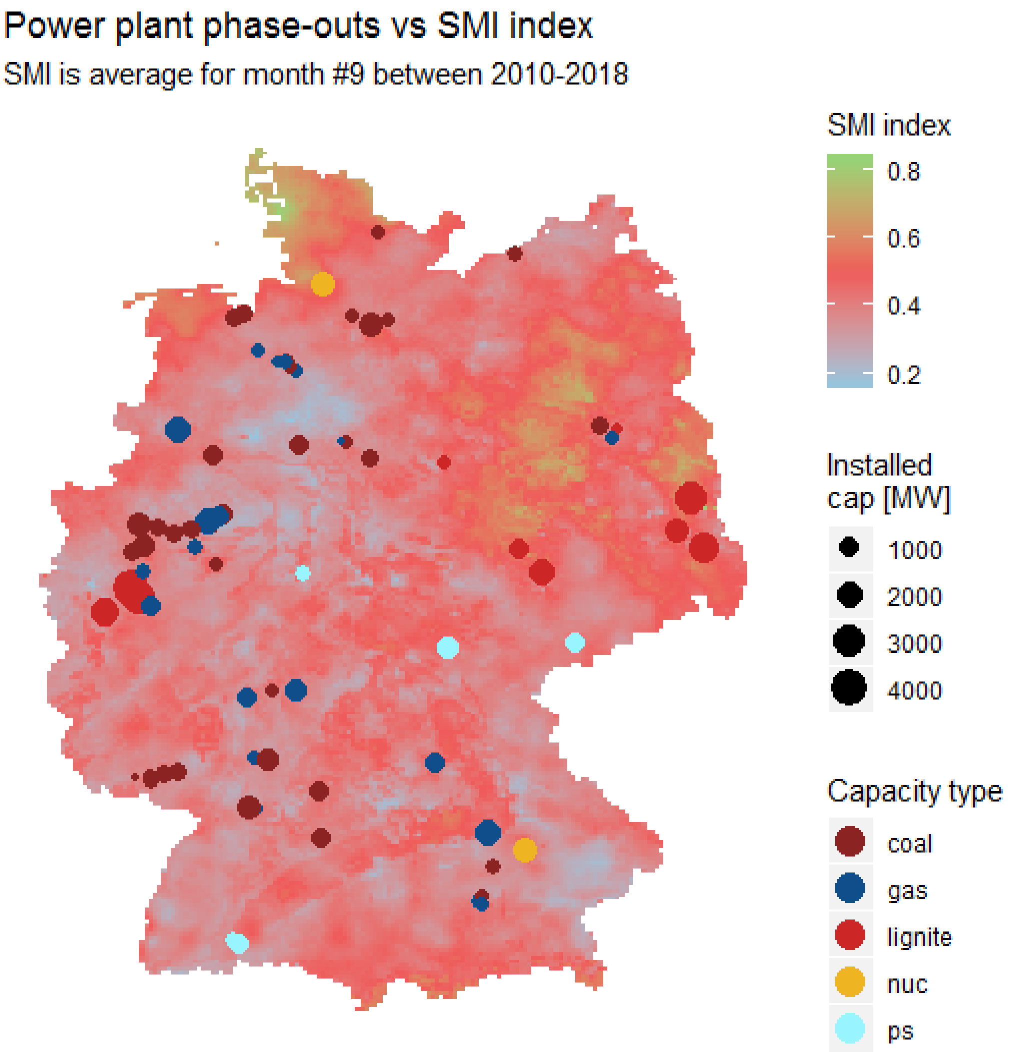
For subsequent analysis we testing for long-run relationship between temperature and drought:

City	State	Station ID	$r = 0$ test	$r = 0$ critical value	$r \leq 1$ test	$r \leq 1$ critical value	
Potsdam	BB	3987	429.96	23.52*	60.71	11.65*	cointegrated
Berlin	BE	403	343.65	23.52*	27.11	11.65*	cointegrated
Ellwangen	BW	1197	177.66	23.52*	20.94	11.65*	cointegrated
Augsburg	BY	461	177.66	23.52*	20.94	11.65*	cointegrated
Hof	BY	2261	386.06	23.52*	58.34	11.65*	cointegrated
Altenkirchen	MV	232	429.96	23.52*	60.71	11.65*	cointegrated
Marnitz	MV	3196	349.44	23.52*	33.28	11.65*	cointegrated
Lingen	NI	3023	262.19	23.52*	48.86	11.65*	cointegrated
Essen	NW	1303	356.80	23.52*	69.31	11.65*	cointegrated
Alzey	RP	150	85.66	23.52*	14.18	11.65*	cointegrated
Erfde	SH	1266	264.38	23.52*	54.07	11.65*	cointegrated
Wadgassen	SL	460	136.18	23.52*	25.22	11.65*	cointegrated
Chemnitz	SN	853	388.89	23.52*	47.53	11.65*	cointegrated
Plauen	SN	3946	303.87	23.52*	34.43	11.65*	cointegrated
Magdeburg	ST	3126	366.50	23.52*	22.79	11.65*	cointegrated
Harzgerode	ST	2044	228.42	23.52*	26.34	11.65*	cointegrated
Erfurt	TH	1270	351.62	23.52*	21.66	11.65*	cointegrated
Gera	TH	1612	337.72	23.52*	31.22	11.65*	cointegrated

significance levels: * 1%, ** 5%, ***10%

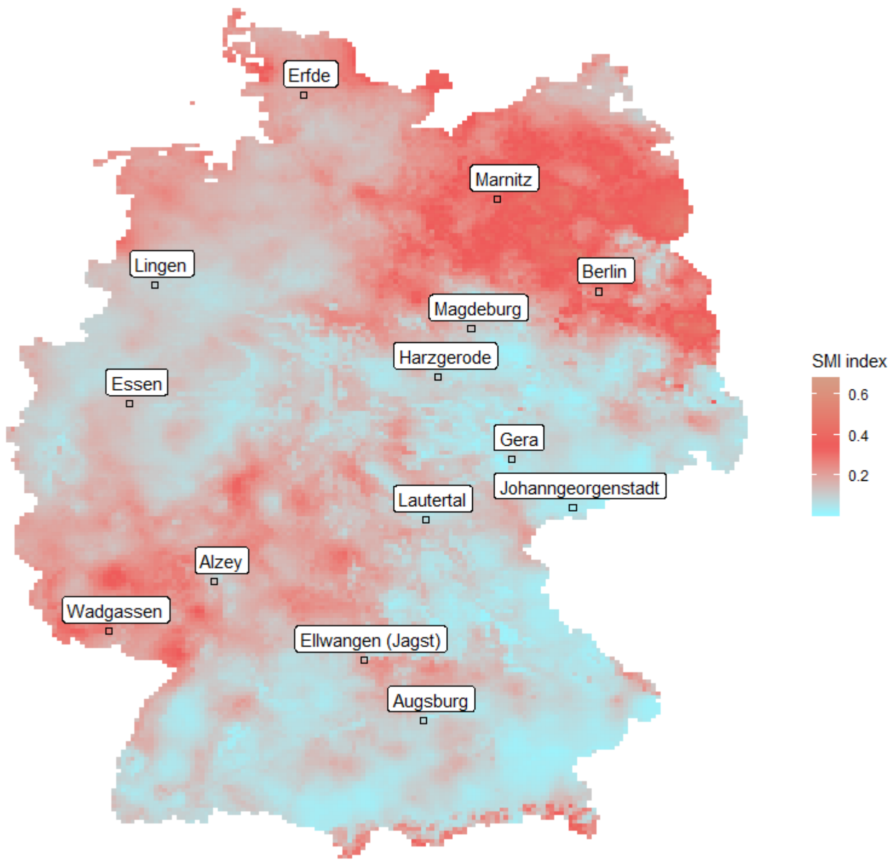
Data: Droughts vs Outages

1 | 2 | **3** | 4

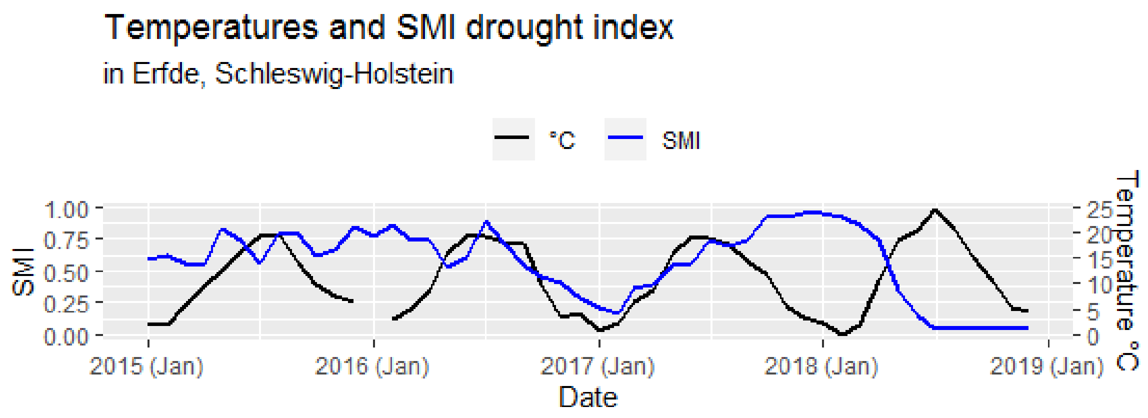


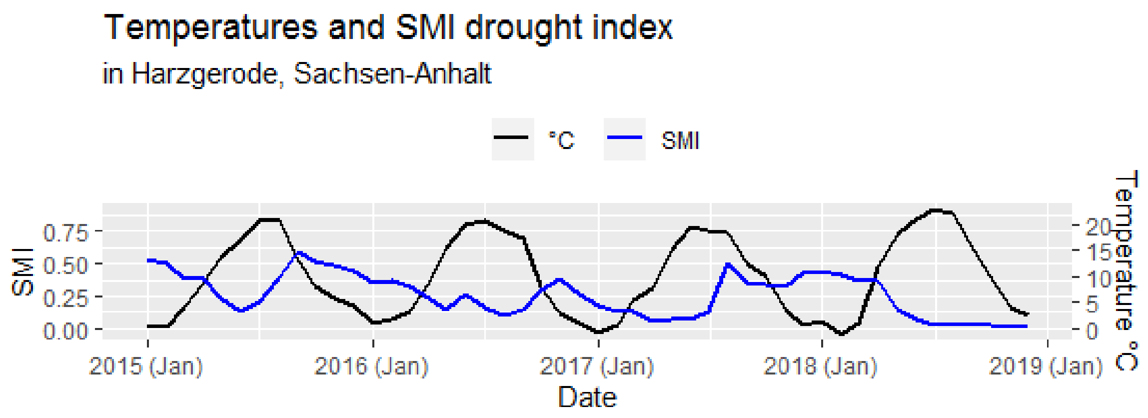
Location of weather stations (temperature)

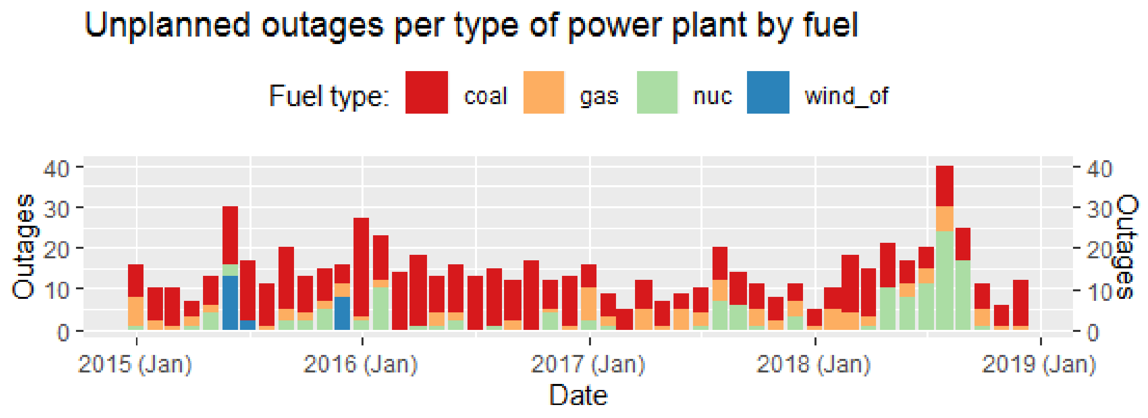
SMI is monthly average between 2018.04.01-11.01

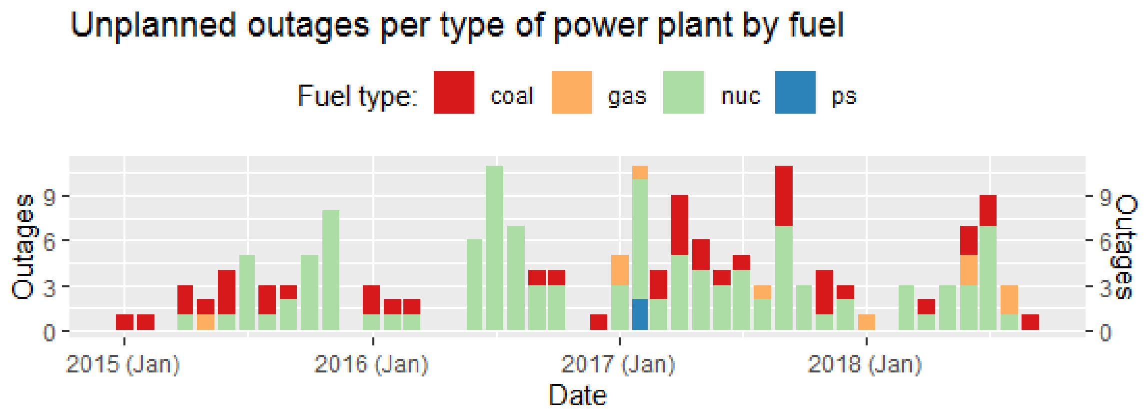


Data: Droughts vs Outages





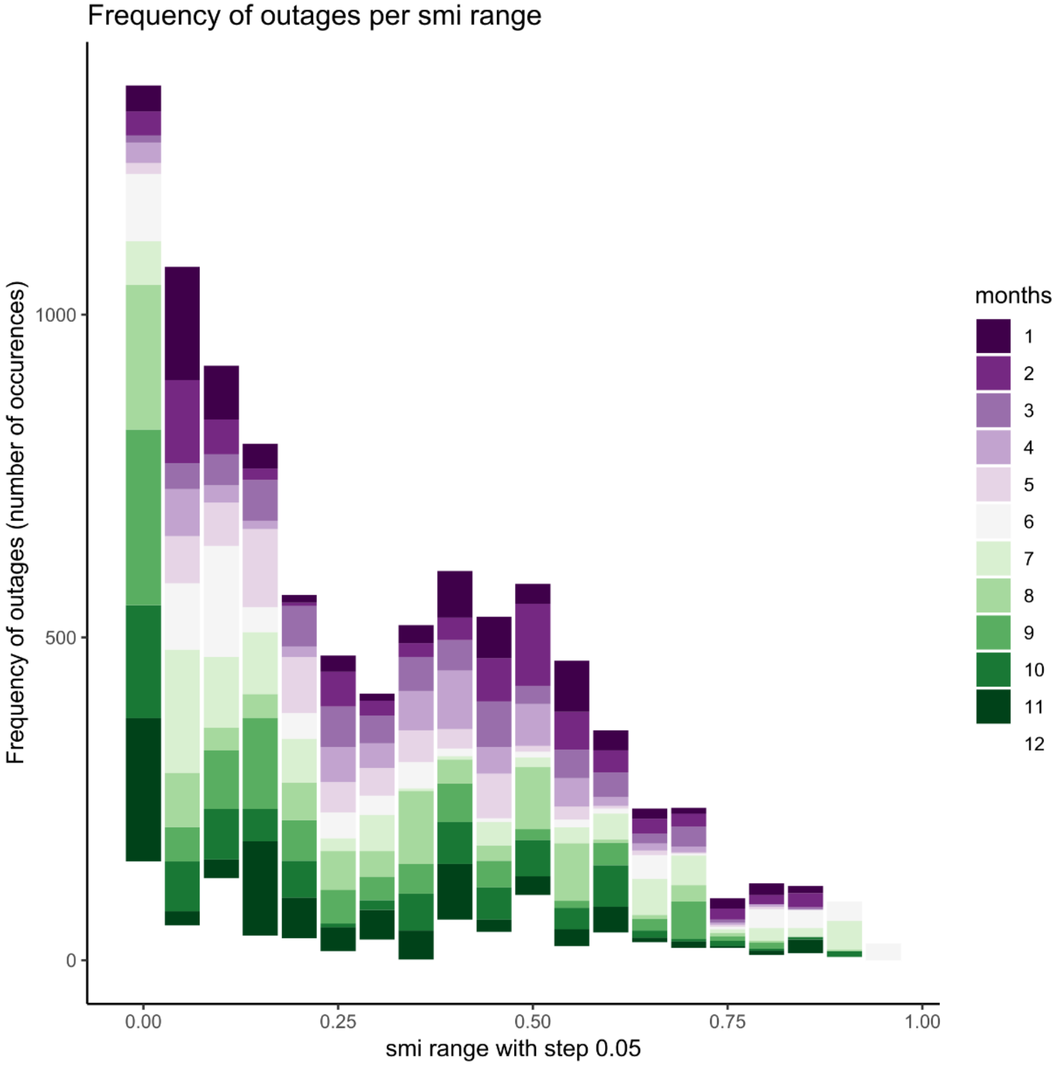




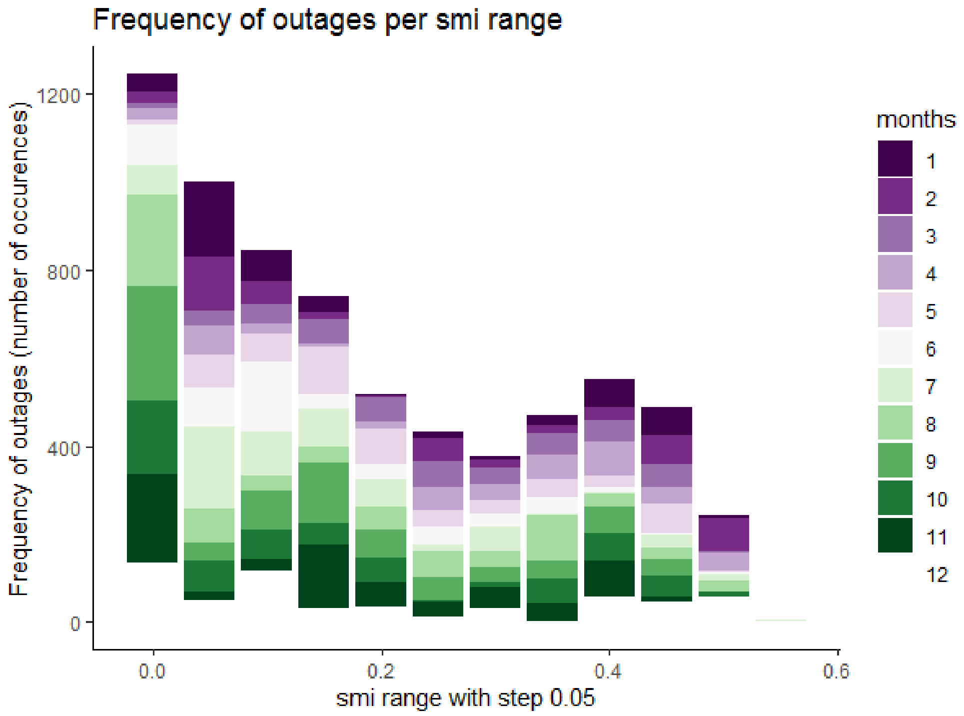
Data: Droughts vs Outages

1 | 2 | **3** | 4

All locations and outages in them



Locations are filtered: only locations for which SMI 2015-2018 was below 10% percentile of SMI values for reference period 1951-2000.



Data: Control Area Balances vs Temperature

Control area: Ampiron

	group	LLC Statistic (lag) [p-value]	IPS Statistic (lag) [p-value]	individual	Hardi Statistic [p-value]
level	t, cab_n, cab_p	-1.985 (27-30) [0.024**]	-33.136 (5-28) [0***]	t t (1st diff)	3.212 [0.0006] -1.062 [0.8559]
intercept	t, cab_n, cab_p	-3.562 (5-28) [0***]	-33.136 (5-28) [0***]	cab_n cab_n,(1st diff)	4.861 [5.821e-07***] -1.115 [0.8677]
intercept and trend	t, cab_n, cab_p	-5.028 (5-28) [0***]	-35.296 (5-28) [0***]	cab_p cab_p (1st diff)	0.025 [0.4897] -1.062 [0.8559]

Significance codes: ***0, **0.05, *0.1
Lag lengths are determined via AIC and in parentheses. LLC AND IPC unit root tests have a null hypothesis that the series has a unit root against the alternative of stationary. Hadri test has null hypothesis of stationarity against the alternative of unit root.

Granger causality test 2015-2017 (lag=1)

Null Hypothesis:	Obs	F-statistic	p-value
t Granger cause cab.pos	5590	31.59	1.996e-08 ***
cab.pos Granger cause t	5590	2.716	0.0994
t Granger cause cab.neg	5590	35.896	2.211e-09 ***
cab.neg Granger cause t	5590	2.4195	0.1199
wnd Granger cause cab.pos	5590	6.1237	0.01337 *
cab.pos Granger cause wnd	5590	1.2783	0.2583
wnd Granger cause cab.neg	5590	39.631	3.301e-10 ***
cab.neg Granger cause wnd	5590	12.683	0.000372 ***
pv Granger cause cab.pos	5590	11.756	0.000611 ***
cab.pos Granger cause pv	5590	6.2852	0.0122 *
pv Granger cause cab.neg	5590	4.5917	0.03217 *
cab.neg Granger cause pv	5590	25.444	4.699e-07 ***

Signif. codes: *** 0.001, ** 0.01, * 0.05

Unit root and co-integration tests

&

Granger causality tests

marks up two values that are related by a phenomenon that X_i causes Y_i if the past values of X_i help to predict the changes of Y_i.

$$Y_i = \gamma_0 + \sum_{z=1}^{p} \gamma_z Y_{t-z} + \sum_{i=1}^{q} \lambda_i X_{t-1} + \mu_t$$

$$X_i = \varphi_0 + \sum_{z=1}^{p} \sigma_z X_{t-z} + \sum_{i=1}^{q} \psi_i Y_{t-1} + \varepsilon_t$$

- Temperature changes always granger-cause changes in control balances, and the vice versa relation is non-significant.
- On contrary, the PV and wind in-feed time series do not show the clear granger-causation in one direction.

Takeaway and work in progress

"The cost of equipping 3-5 power plants with cooling towers would be 165-275 million EUR. The lifetime of thermal power plants is about 40 years. It is assumed that the associated cooling towers also have this service life. The costs thus amount to 4 - 8 million Euro per year." [Tröltzsch et al., 2012]

"As for many cost data, it is difficult to obtain reliable and generalizable cost information for cooling systems which also work under higher ambient temperature…" [Altvater et al, 2012]

The costs of alternative cooling system:

- capital costs of the technical equipment
- annual operation and maintenance costs
- costs of cooler system-induced efficiency losses in energy generation

"Specific site, ground, water availability and costs, water and air regulations, distances between the single components of the system, size of the plant, type of plant, bargaining power of the respective companies, climate etc."

"By the end of this century, drought and heat damage in Europe will comprise 67% and 27%, respectively, of all hazard impacts to the energy sector (now 31% and 9%, respectively)." [Forzieri et al., 2018]

Takeaway and work in progress

Takeaway:

- Climate change poses negative effects and additional stresses on the electricity system.
- Hydrological droughts and water scarcity become more intense.
- Patterns in tertiary reserves may signal for a need in faster transformation of the electricity system.

Work to do:

- Analysing meteorological data at each power plant location. ✓
- Statistic and econometric analysis… ✓
- Build technology-specific impact response functions…
- Assess risk-adjusted economic costs of climate change for the power system …

Thank you for your attention

Looking forward to your questions

Literature

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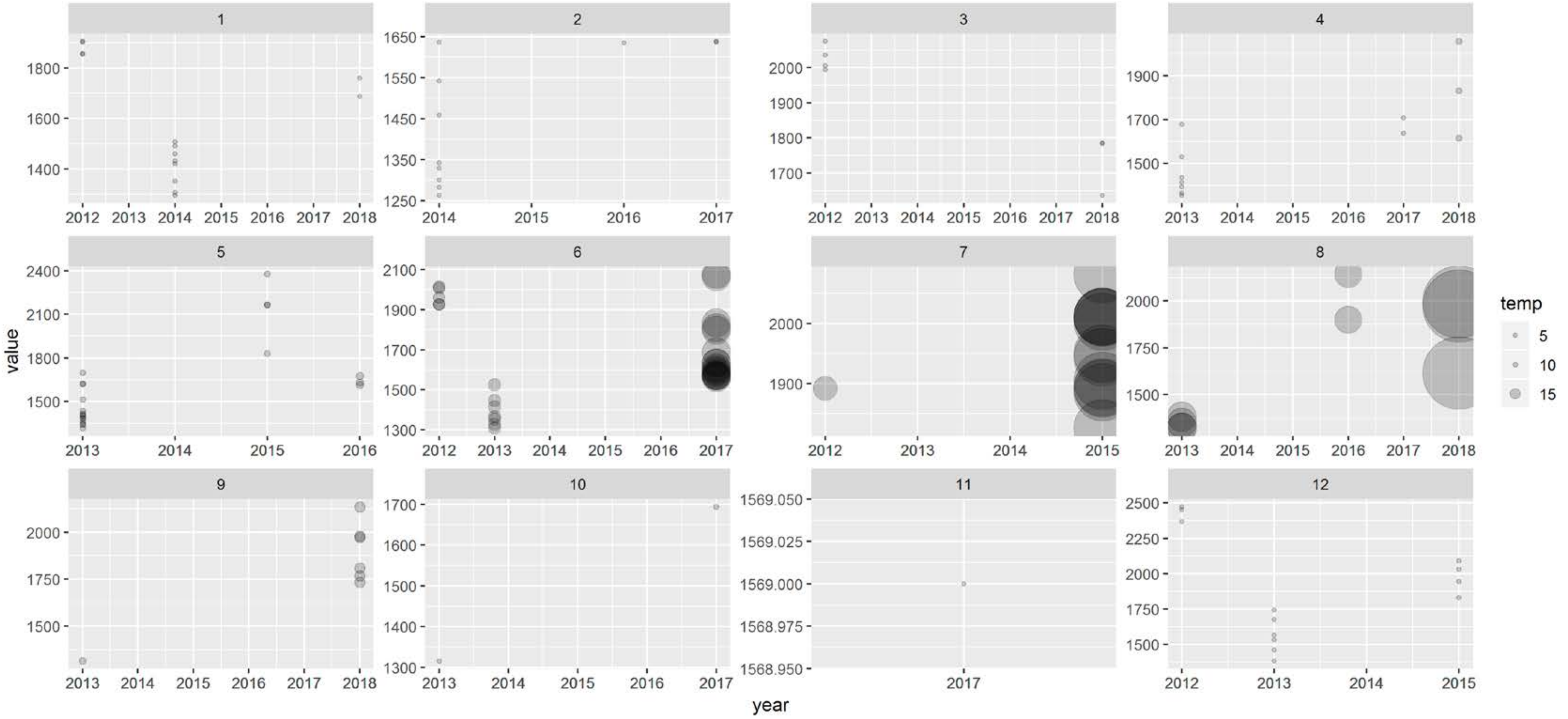
Data: Tertiary Reserves vs Temperature

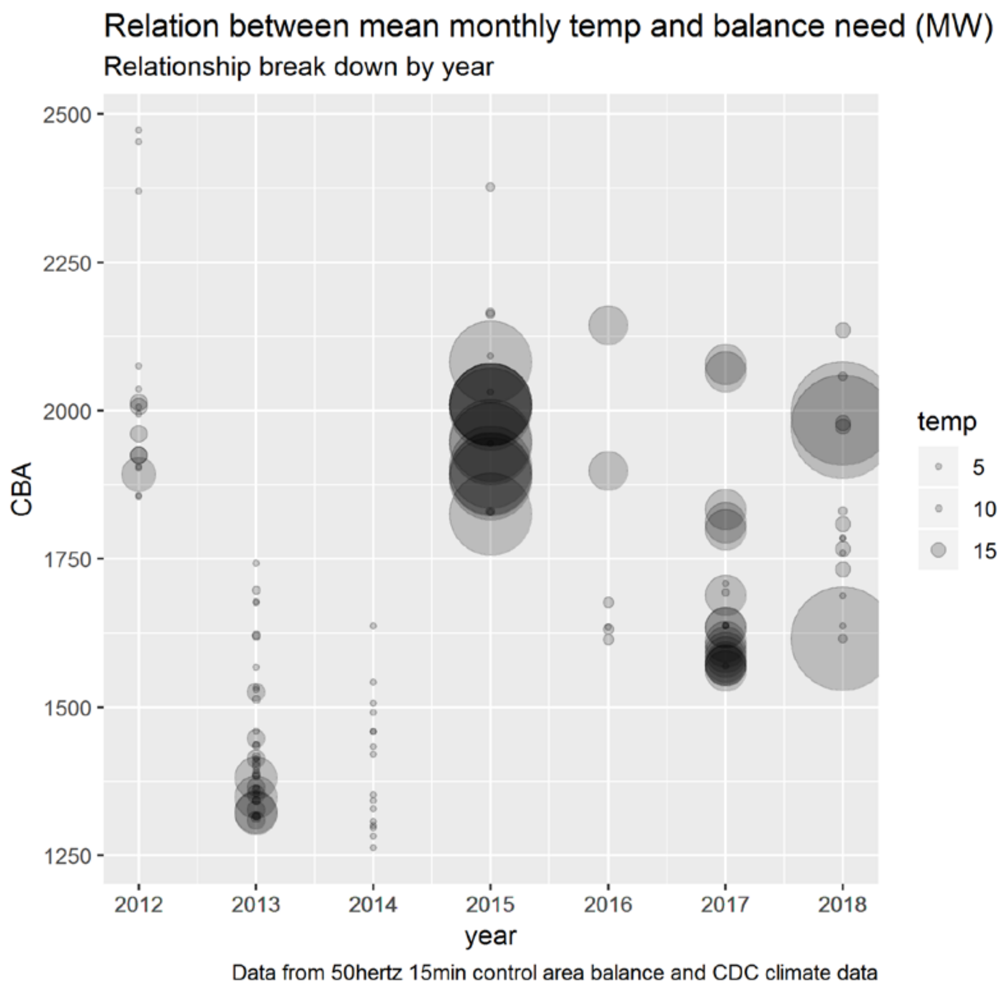
1 | 2 | **3** | 4

Control area: 50Hz



Data: Tertiary Reserves vs Temperature

Control area: 50Hz



- De-rating or shut-down were not associated with low water levels at the intake but rather elevated temperatures of effluent or at cooling water in-take. [Cook et.al., 2015]
- Focus: once-through and recirculating cooling plants with cooling ponds.

KKW Neckarwestheim: both continuous and recirculating cooling systems:

- Temperatures of water exceed allowed values for fishes already above power plant site. Reaching 26° C in the extreme summer of 2003 and 2006.
- Regulations define maximum water intake (<30°C) and outtake temperatures (<28°C) [EnBW, 2017]