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Climate variability and energy security in Italy

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SUMMARY Energy and water security are arguably among the most important present-day societal and environmental challenges. Amidst the early signs of human induced climate change, both energy and water management systems are undergoing sizeable transformations. In addition, water is a critically important resource for hydro- and thermoelectricity generation; fossil fuel extraction/processing, and for the production of biofuels. This paper analyses inter-dependences of energy and water in the Po River Basin District (PRBD) situated in the Northern Italy, the most industrialised part of the country and home to 17 million people. Specifically, we explore the role of climate variability as a part of the structural vulnerability of thermo- and hydroelectricity generation.

Keywords: Energy security, water security, climate variability, hydro- and thermoelectricity generation, Po River Basin

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1. INTRODUCTION

Energy and water security are arguably among the most important present-day societal (and environmental) challenges (WEF 2014). Amidst the early signs of human induced climate change, both energy and water management systems are undergoing sizeable transformations.

The EU Directive 2009/28/EC (and before in the Directive 2001/77/EC) and the Europe 2020 strategy set ambitious energy goals and renewable energy targets. In Italy these targets entail increasing the share of renewable energy sources (RES) in the gross energy consumption to 17,0 per cent, and 26,4 per cent in terms of electricity generation. According to the OECD data (OECD, 2012), Italy's total primary energy supply reached, in 2011, 165.1 million tonnes of oil equivalent (Mtoe), while the energy intensity of the economy passed from 0.14 to 0.10 tonnes of oil equivalent (toe) per thousand 2005 US dollars of GDP (calculated using PPPs) in the period 1971 – 2011 (OECD, 2012).

In 2010, thanks to the sizeable incentives and as a result of demand decline amidst economic crisis, Italy was still far away from both targets but exceeded the 2010 milestone and came close to the 2015 milestone. Since then, the exceptional grow of RES in electricity generation set forth (SM Figure 1) and in some months during 2013, with RES replaced surpassing the thermoelectric power generation.

Water is a critically important resource for hydro- and thermoelectricity generation; fossil fuel extraction/processing, and for the production of biofuels. According to the 2012 World Energy Outlook, some 580 billion cubic metres of water are withdrawn annually for energy production (IEA, 2012). On the opposite side, energy, and in particular electricity, is important for water transportation, treatment and distribution. In 2011, some 8 per cent of the Italian electricity demand was represented by the requirements of the water treatment and distribution sector.

The Italian energy mix has been historically dependent on hydropower and fossil fuels. In the last few years, the consistent investments on renewable energy sources, allowed these sources to reach a share of 11.7 per cent of the total primary energy supply (OECD, 2012). The national strategy aimed at achieving these results has been modelled on a system of incentives aimed at boosting the renewable energy sector. The incentive scheme has been operative since 2002 and was structured on a complex Green Energy Certificate compliance market in combination with a feed-in-tariff system (Farinosi, Carrera, Mysiak, Breil, & Testella, 2012). By the end of 2012 and the beginning of 2013, the Italian Government phased out the compliance market for certificates replacing it with a feed-in-tariff system determined through auctions and tenders (APER, 2012).

This paper analyse inter-dependences of energy and water in the Po River Basin District (PRBD) situated in the Northern Italy, the most industrialised part of the country and home to 17 million. The PRBD, extending over 71.000 km^2 is Italy's largest (single river) basin and the economically most important area. More than one third of country's industries producing 40 per cent of the national GDP are located in the basin area (AdBPo, 2006).

Over the past decade or so, the thermo- and hydroelectric generation experienced a downside to a large extent because of the decline of average water endowment and climate variability. The drought spells of 2003 and 2006-2007 have illustrated the vulnerability of the Italian electricity production sector to climate variability and change (AdBPo, 2006). Although the PRBD counts to the better water-endowed regions of Italy, the over-commitment of water resources had led to critical water shortages for agriculture, energy production, and to a minor extent to public water supply. In 2003, the extreme water scarcity had provoked the activation of the *Electricity System Security Emergency Plan*.

In this article we explore the role of climate variability as a part of the structural vulnerability of the energy systems. The article is structured as follows: Section 2 explains the sources of analysed data and assumptions made in the analysis. Section 3 reviews the vulnerability of thermo- and hydroelectricity generation to climate variability. Section 4 draws the conclusions and policy implications of the analysis. Additional information is included in the Supplementary Material (Annex).

2. MATERIAL AND METHODS

The power plants, both thermo- and hydroelectric (TE, HE), that are situated in the PRBD were extracted from the UDI *World Electric Power Plants* (WEPP[1]) database. WEPP is a global inventory of existing and planned electric power generating units. It contains information about the location and technical design of power plants (PP) of all sizes and technologies operated by regulated utilities: power companies, industrial and commercial auto-producers across the world (UDI WORLD, 2013). The WEEP version we had an access to localises the energy plants by municipality in which they are situated, and in addition but in some case only by zip code. The municipalities are not free of typographical errors or differ from the official administrative names. Hence first we have corrected and geo-referenced the sub-set of database containing the plants within the PRBD (Figure 1). (See also the Supplementary material (SM) Table 1 and SM Map 1 that show the number of plants and installed capacity across the provinces of the PRDB).

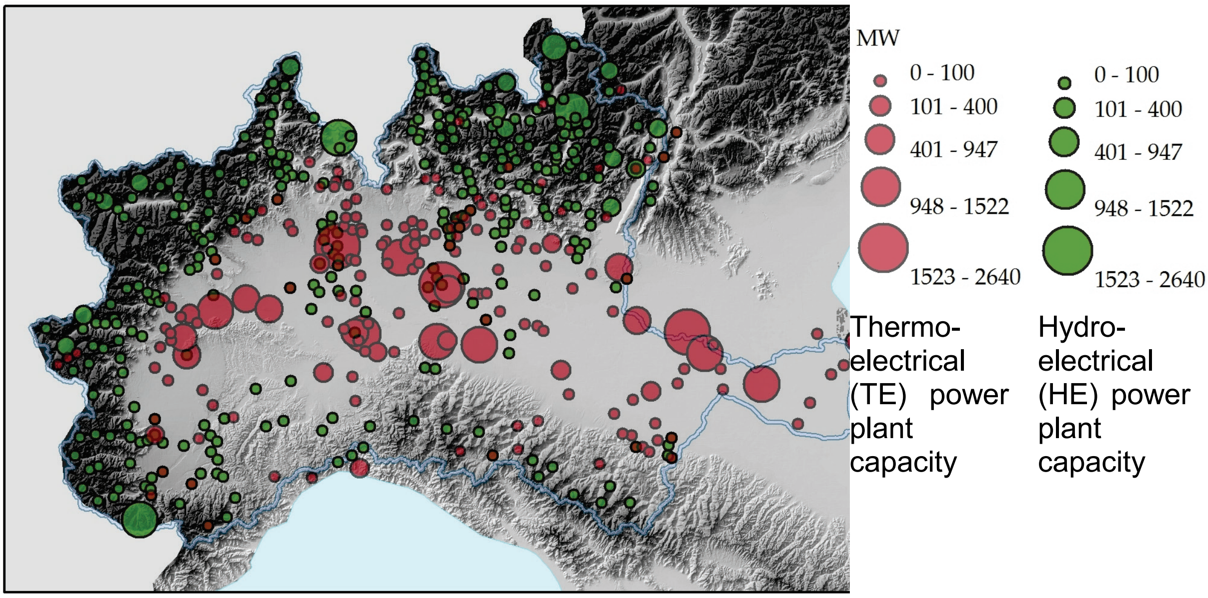

Figure 1 Installed capacity (in MW) of the TE (*red*) and HE (*green*) power plants in the PRBD. *Source*: own elaboration based on the WEPP data.

We use the statistical data of energy generation collected by the statistical bureau (ISTAT[2]), the energy market regulator[3], and the Italian electricity transmission system

[1] www.platts.com/products/world-electric-power-plants-database
[2] L'Istituto nazionale di statistica [National Institute for Statistics] www.istat.it
[3] Autorità per l'energia elettrica il gas ed il sistema idrico (Regulatory authority for Electricity, gas and water services] www.autorita.energia.it

operator[4]. Plant-specific indications about energy produced and cooling water demand were extracted from the *environmental declarations* (ED) of each power plant enrolled in the EU Eco-Management and Audit Scheme (EMAS)[5]. The EDs are available for the period 2007-2012. Water licences (i.e. permitted volume of water for cooling purposes) were obtained from the databases managed by respective water authorities. In Italy, the management of water resources is to a large extent competence of the Regions (first-level administrative divisions of the state). The databases of water entitlements of Piedmont, Lombardy and Valle d'Aosta were analysed for the scope of this paper. The nominal value of water entitlement indicates the *maximum permitted* volume of water that may differ from the actual water demand/withdrawal. *Environmental flow* (EF) requirements were defined for the purpose of this paper as 20 per cent of the average flow at the water withdrawal point or nearby upstream. Daily water flows of the water bodies from which water is abstracted for cooling the TE plants were obtained from the database of the Regional Environmental Protection Agency (REPA) *Emilia Romagna*. The flow-duration curves (FDC) were estimated for the period 2000-2011.

3. CLIMATE VARIABILITY AND ELECTRICITY PRODUCTION

3.1 THERMO-ELECTRICITY PRODUCTION

The thermoelectric (TE) power generation is concentrated in the Northern Italy, and predominantly in the regions which are entirely or to a large extent comprised in the PRBD (i.e. Lombardy, Piedmont, and Emilia Romagna). In 2012 these three regions have generated around 30 per cent of the *national* TE gross production, a 7.6 per cent larger share than in 2000 (Table 1). Over the period 2000-2012 the number of TE plants in PRDB regions increased almost fourfold, while the gross installed capacity grew by around 80 per cent (double as much as in Italy as whole). Whereas the production of TE over the past 12 years slightly declined in Italy, it rose by 31 per cents in the PRBD regions. The concentration of power plants in the Northern Italy is not surprising given the large share of population and industrial assets located there.

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[4] Terna S.p.A. www.terna.it

[5] EMAS is a management instrument developed by the European Commission for companies and other organisations to evaluate, report, and improve their environmental performance, ec.europa.eu/environment/emas

Region	Nr of plants	Change to 2000 (%)	Gross Capacity [MW]	Change to 2000 (%)	Gross Product. [GWh]	Change to 2000 (%)
Piedmont	392	*253*	5.976	*149*	17.021	*73*
Lombardy	831	*454*	13.376	*66*	31.774	*4*
Emilia Romagna	559	*370*	6.923	*80*	20.210	*67*
Total PRBD regions	1.782	368	26.275	*84*	69.005	*31*
Italy	3.553	*301*	81.346	*42,6*	223.153	*-1,0*
PRDB as a % of Italy	*50*	*+7,1*	*32*	*+22,6*	*30,9*	*+7,6*

Table 1 Thermo-electric power plants and electricity production in 2012 in the regions of the PRBD. Based on the data from Terna.

Although the installed capacity swelled by 84 per cent, the gross production increased only by 31. This is partly due to raising capacity and production from renewable energy sources (RES), especially solar energy. From among the PRBD regions, Emilia Romagna displays the most favourable relation between the newly installed capacity and gross production (80 and 67 per cent respectively), whereas in Piedmont and Lombardy the increases in gross production fall far behind the growth in terms of the installed capacity. This is despite the fact that all three regions are in net minus for what concerns the own electricity production and demand. In Italy, the TE generation declined over the analysed period by a percent point.

The distribution of the installed capacity and production is highly asymmetrical. In 2011, around 88 per cent of the installed TE capacity was operated by only 9 companies (Edipower, *Enel*, *E.ON*, *Enipower*, *A2A*, *Iren Energia*, *Edison*, *Sorgenia*, and *Aceaelectrabel*[6]). Moreover, some 83 per cent of the installed capacity and more than 60 per cent of the TE produced the year before were concentrated in just 20 municipalities. Moreover yet, more than 77 per cent of the TE capacity is concentrated in only 18 power plants (PP). This elevated concentration raises concerns regarding systemic risk of production breakdowns in cases of droughts as experienced throughout 2000s. In 2003, the Po river discharge at basin closure (Pontelagoscuro) reached the up-to-date lowest level since the instrumental records (-6.99 m or 270 m3/s or 20 per cent of the average discharge of 1450 m^3/s). In Summer 2003, the average temperature climbed up to 28.6°C,

[6] With exception of *Enipower*, *Sorgenia*, and *Aceaelectrabel* these companies are among the largest companies in Italy (REF)

5°C above the 1969-98 average. Precipitations fell to 73 mm compared to long term average of 140.7 mm. July's precipitation amounted only to 1.7 mm. The suddenly mounted electricity demand and shut down of TE plants were not able to satisfy the cooling water demand led to a series of regional blackouts.

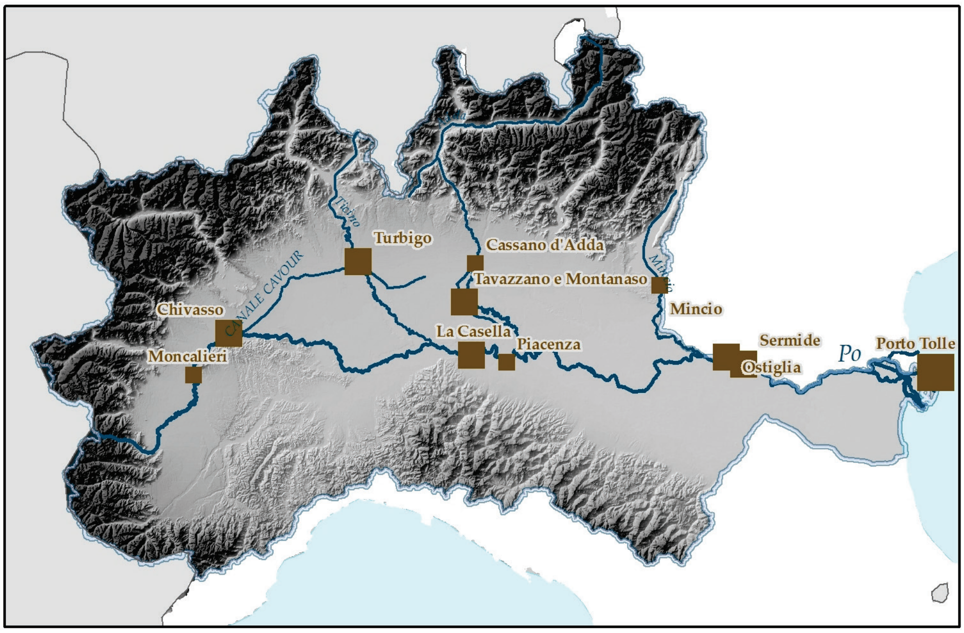


Figure 2: The largest TE plants with wet cooling in the PRBD, all but four using water withdrawn from the Po river (Porto Tolle is currently off-the-grid and not considered in the analysis). The remaining plants use water from Ticino, Adda and Mincio.

Out of the 18 largest TE PP in the PRBD, four are not enrolled in the EMAS scheme and hence the EDs were not available. The *Porto Tolle* plant situated in the delta of Po river, until recently one of the most important TE plants in Italy (installed nominal capacity 2.640 MW), is off-the-grid for the planned conversion to clean coal technology and not included in the analysis. All the remaining (13) installations are based on combined cycle fuelled with natural gas and oil mainly. The total number of burning units amounts to 78. Ten plants are cooled with an open cycle flowing water systems that require, depending on the size, large volume of water. The cooling water demand for these TE plants ranges from 55 to 236 m^3/MWh. Four plants use dry cooling tower technology with much lower water demand.

Hereafter we focus on the 10 TE power plants (Figure 2) with open circuit cooling systems for which data about cooling water demand is available. These PP account for between 40 and 50 per cent of thermoelectricity produced in the PRBD regions. Six of them withdraw water from the Po river while the remaining plants use water from the tributaries of the Po river *Ticino*, *Adda* and *Mincio*. The flow of these rivers is controlled by the regulated releases from the lakes *Maggiore*, *Como* and *Garda*.

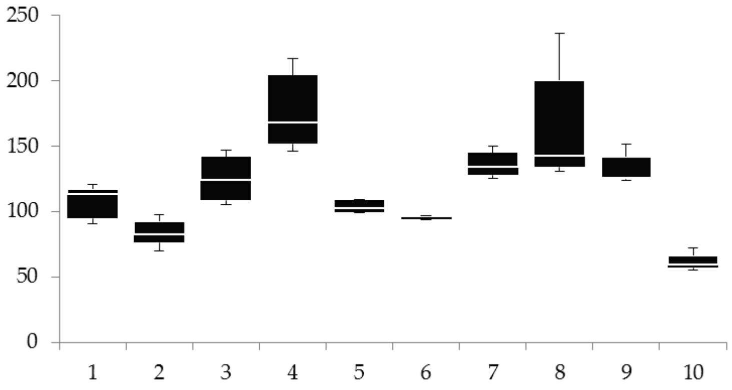


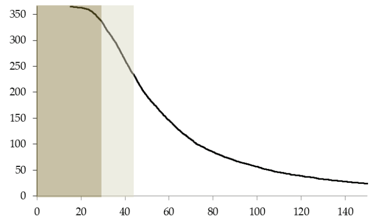
Figure 3 Cooling water demand (in m^3, y-axis) for the production of 1 MWh in the selected TE plants (x-axis) in the PRBD. Only plants are included that are enrolled in the EMAS system. Box-plot diagrams TE plants from left: *Cassano d'Adda*, *Mincio*, *Ostiglia*, *Tavazzano e Montanaso*, *Piacenza*, *Sermide*, *Turbigo*, *La Casella*, *Moncalieri*.

On average, the production of 1 MWh requires some 110 m^3 of cooling water (lower quartile ~94 and upper quartile ~142 m^3/MWh). The TE plants also need demineralised and potable water for other than cooling purposes but their volumes are negligible compared to the cooling water demand. Based on the information contained in the EMAS environmental (impacts) declarations (EDs), there is a slightly declining trend of the cooling water demand, driven by technological improvements and improved plant operation. This trend is obscured by non-linear relationship between energy produced and water withdrawn for cooling. Cooling water demand depends from the effective working hours (the information about which is not publicly accessible), and the number of times the power plant units are shut down and started up. In the warming up and shutdown phases, the TE plants do not produce electricity but need cooling water. Figure 3 shows the cooling water demand per MWh produced for ten among the largest TE plants in the PRBD.

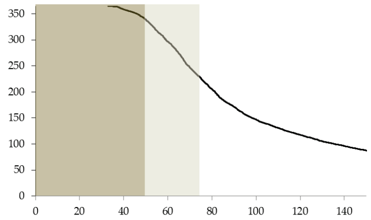
Figure 4 shows the *flow duration curve* of the water bodies from which the TE plants are served, close to the points at which the water is withdrawn. Each curve shows how many days a year a certain volume of flow is present at any given point of the analysed water courses. For the two analysed scenarios (S1 and S2) the Figure 2 shows the volume of waters subtracted either as a result of environmental (ecological) flow requirements and/upstream withdrawals, however constrained.

Utility	TE plant	Power (MW)	Water entitlements		Gross TE produced (GWh)					Cooling water abstracted ($x10^6$ m^3)					N. days shortage		Energy loss MWh	
			water body	*m3/s*	*2007*	*2008*	*2009*	*2010*	*2011*	*2007*	*2008*	*2009*	*2010*	*2011*	*S1*	*S2*	*S1*	*S2*
A2A	Cassano d'Adda	995	Adda (c. Muzza)	14	4547	3923	3045	2763	2520	404	377	340	305	279	6	69	73	843
A2A	Mincio	380	Mincio	9	1717	1700	1293	919	906	117	136	111	74	86	97	116	445	532
E.ON	Ostiglia	1482	Po	30	6508	6032	2946	3280	4327	666	694	415	411	498	9	39	156	677
E.ON	Tavazzano Montanaso	1460	Adda (c. Muzza)	43	6716	5375	3298	2669	2102	951	876	686	430	312	53	129	945	2301
Edipower	Chivasso	1179	Po (c. Cavour)	*18.5**	5479	4921	3060	2340	2450	474	420	296	249	244	26	152	390	2282
Edipower	Piacenza	855	Po	*11.3**	3277	3092	2643	2410	2010	297	283	248	228	191	2	32	18	281
Edipower	Sermide	1154	Po	25	5085	4718	2737	3055	2057	619	614	397	386	280	9	38	122	516
Edipower	Turbigo	1755	Ticino (Naviglio Grande)	23	1920	2510	2549	2435	2229	417	395	349	320	281	49	111	328	743
Enel	La Casella	1400	Po	*35**	*6815***	*7774***	*3678***	*5564***	*5281***	813	923	531	702	622	7	39	142	791
Iren Energia	Moncalieri	800	Po	*13**	2355	2848	3679	4005	4433	251	262	298	310	331	19	119	185	1156

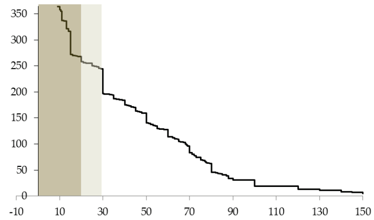
Table 2: The largest ten water cooled thermo-electric power plants in the PRBD regions; their TE production and cooling water consumption over the period 2007-2011, simulated number of days with low river flow and the ensuing energy losses. Scenario 1 (S1) refers to environmental flow requirements at the level of 20 per cent of average flow, whereas the S2 considers higher threshold (40 per cent) and takes into account to the upstream withdrawals and likely future flow decline. The TE produced and cooling water withdrawn are based on the *environmental declaration* (ED) of each plant. Water entitlements have been obtained from the water registers of the regional water authorities, or estimated (where indicated as *) as the highest reported withdrawal over the analysed period, increased by 20 per cent. Where not both net and gross TE production is indicated in ED, we approximate the missing data using 0.95 and 1.05 conversion coefficients (**).



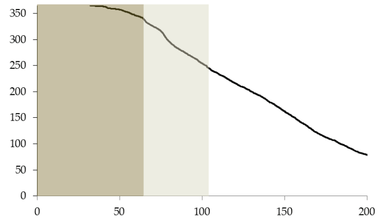
Moncallieri (Po)



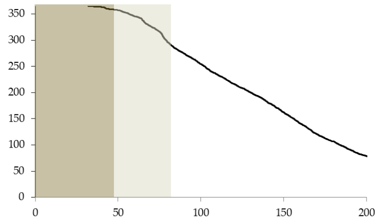
Chivasso (Po - Canal Cavour)



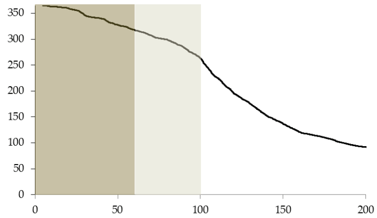
Ponti su Mincio (Mincio)



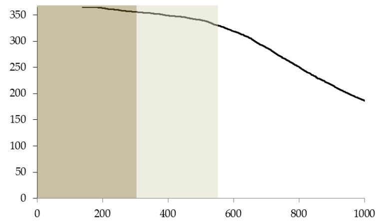
Tavazzano e Montanaso (Adda- Canal Muzza)



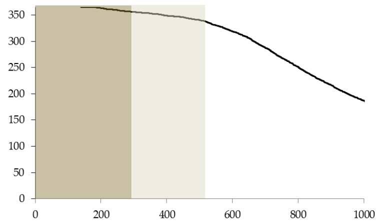
Cassano d'Adda (Adda- Canal Muzza)



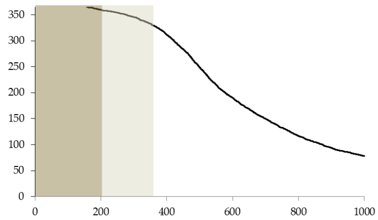
Turbigo (Ticino – Naviglio Grande)



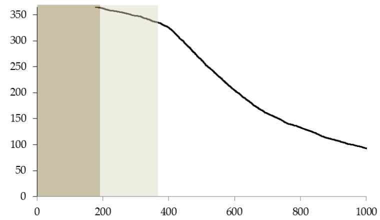
Ostiglia (Po)



Sermide (Po)



La Casella (Po)



Piacenza (Po)

Figure 4: *Flow duration curve* of water bodies at the points cooling water is withdrawn to supply the major TE power plants in the PRBD. River discharges (m^3) on the x-axes compared to a number of days (y-axes) at which any given volume of flow is equalled or exceeded. Dark shaded area marks the environmental flow requirements (S1: 20 per cent of the average flow) and the light shaded area (S2: 40 per cent of the average flow) shows the flow that might be compromised by either upstream water uses and/or medium-term alteration of flow regime. *Source*: own elaboration based on the RNPA data.

Our analysis (Table 2) reveals that between 6 and over 21 per cent of the annual thermoelectricity production of the ten analysed TE PP can be compromised by low river flow. This corresponds to between 2 and 11 per cent of the TE generation in the PRBD regions. These estimates are conservative as they reflect long term river flows. Short-term, drought induced reductions of river flow that affect, individually or collectively, the flow or water bodies which serve the major TE installation in the river basin can lead to larger production breaks.

3.2 HYDROELECTRIC GENERATION

The kinetic energy contained in natural water flow is a renewable, carbon dioxide emission-free and easily exploitable source of energy. Making use of water to generate electricity is a conventional water use, analogous to irrigation or cooling, expect for it does not 'consume' water nor alter its physical or chemical properties. The hydroelectricity generation however requires structural modification of water courses and, in the case of larger plants, a construction of water reservoirs.

Four PRBD regions account for more than a half of the installed hydropower capacity and hydro-electricity production in Italy (Table 3). These shares did not change much over the past 12 years. Yet although the capacity in the district grew on average by one per cent point per year, the net hydroelectricity produced remained below the 2000 level for all years except 2011 (SM Figure 6).

In Italy, the number of hydroelectric power plants grew between 2000 and 2010 at an annual average rate of 1.3 per cent but the installed capacity increased only by 0.7 per cent per year. In PRBD, the installed gross capacity has increased steadily from 10,210 MW in 200 to 11,285 MW in 2012. In 2012 Lombardy produced 10,646 GWh and Piedmont 7,113 GWh, respectively 49 and 33 percent of the total hydropower production in the PRBD regions. The number of HPP increased from 839 in 2000 to 1,273 in 2012 (Terna, 2000-2012).

Region	**Nr of plants**	**Change to 2000** (%)	**Gross Capacity** [MW]	**Change to 2000** (%)	**Gross Product.** [GWh]	**Change to 2000** (%)
Piedmont	635	*50*	3.681	*17*	7.113	*-9*
Valle d'Aosta	97	*80*	921	*11*	3.063	*8*
Lombardy	428	*43*	6.039	*7*	10.646	*-19*
Emilia Romagna	113	*82*	645	*6*	895	*-27*
Total PRBD regions	1.273	*52*	*11.285*	*11*	*21.716*	*-13*
Italy	2.977	*51,5*	22.249	*7,7*	43.854	*-14*
PRDB as a % of Italy	*43*	*0,3*	*51*	*1,0*	*50*	*1,0*

Table 3 Hydropower and hydro-electricity production in 2012 in the regions of the PRBD. Based on data Terna.

The hydroelectricity generation is highly sensitive to extreme events at the lower bound of climate variability. In particular, we have found a strong correlation between HE production and river flow at the closure of the basin. Similar results were found in the western United

States and elsewhere (Harto and Yan, 2001). In contrary, there is no correlation between the observed precipitation and HE production. The SM Figure 7 shows the association between the annual net HE production and the average river flow at the Pontelagoscuro, both expressed as quotients of 12-years-average (2000-2012). The high correlation (Pearson's r 0.86) shows similar patterns of river flow at the basin's outlet and the HE production, which is the basis of the Harto and Yan (2001) rough estimation model. The close correlation is somehow counter-intuitive given the steady increasing installed hydropower capacity and the variability of the flow regimes of the Po river tributaries. It may be explained to some extent by the ample flow regulation capacity in the district imparted by the large regulated reservoirs and lakes. Furthermore, Harto and Yan (2001) hypotetise that the ratio of low to average river flow set equal to the ratio of drought-compromised to average HE production would reasonable represent the worst-case scenario. Conrary to their finding, we observe a larger than proportional decline in HE production in the drought years (SM Figure 7).

4. CONCLUSIONS

We have shown that thermo- and hydroelectricity (TE, HE) production in the PRBD is amply vulnerable to climate variability and change (see also Mysiak et al. 2013). Given that around a third of the national TE production, and a half of the national HE production is generated in the PRBD, any changes to the average water availability in the District and the prospects of more frequent drought spells have important implications for national energy security. A foretaste of how important the PRBD is was felt during the intense and prolonged droughts during the 2000s.

Over the past decade, the TE production in the PRBD grew at a much lower rate that the installed capacity. Some of the most recently built TE plants utilise air-cooling technology and consequently are less reliant on steady supplies of large volumes of cooling water. The ten largest water-dependent TE plants, however, account together for around 40-50 per cent of annual TE production. They require one average 110 m^3 per MWh generated. Even if they reduced (slightly) their cooling water demand over the analysed period, we estimated that 6 to 21 per cent of their aggregate average annual production is susceptible to risk even under fairly conservative assumptions. This translates to 2 to 11 per cent of the total TE production in PRBD regions.

The HE production is even more susceptible to production breaks due to low river flows. This is manifested by the declining trend in hydroelectricity production, despite increased installed generation capacity. The climate projections for PRBD provide a doom prospect to what used to be and partly still is water-abundant river basin district. If the decline of annual water endowment of the PRBD continues, Italy may face an additional burden to meet its renewable energy goals.

5. ACKNOWLEDGMENTS

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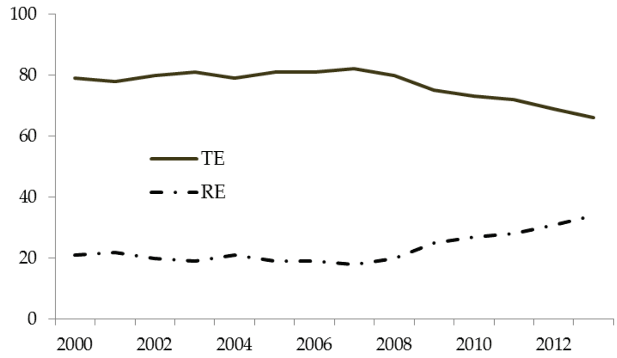
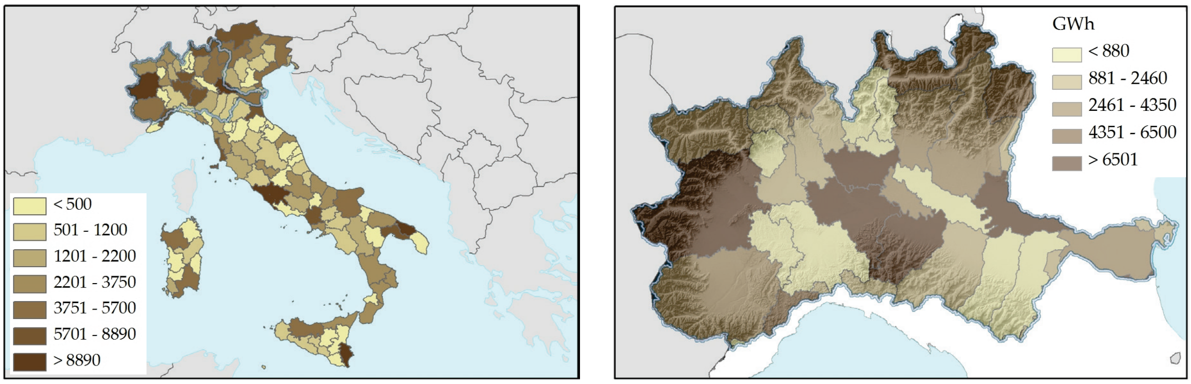
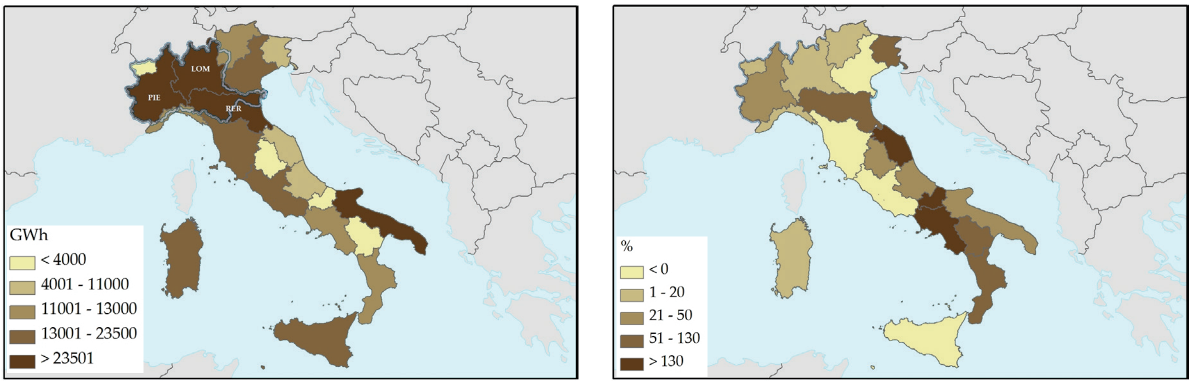
7. SUPPLEMENTARY MATERIAL



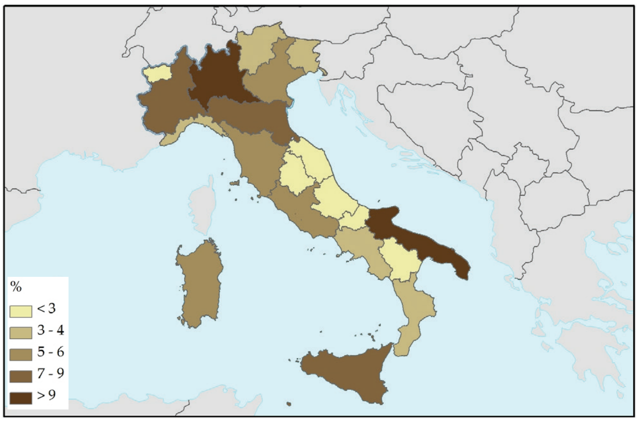
SM Figure 1: Gross electricity production from the thermoelectric (fossil-fuel, TE) and (all) renewable sources (RE) in Italy. Own elaboration based on EAG data.



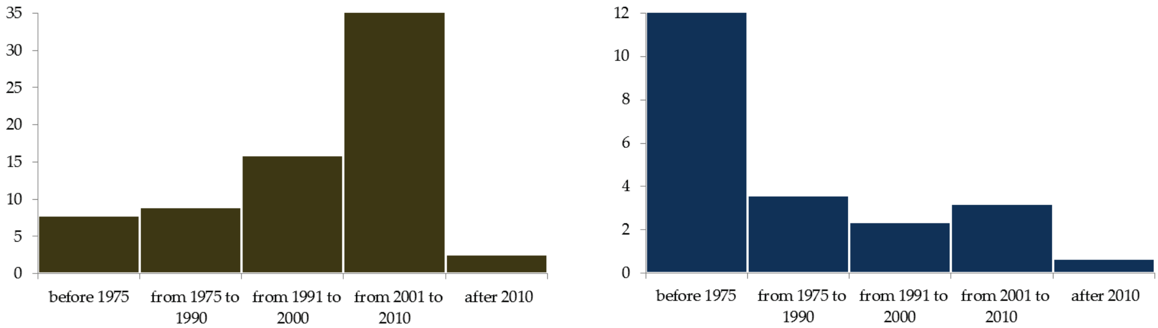
SM Figure 2: The production of electrical energy (EE, in GWh) by provinces; (left) all Italian provinces, (right) the provinces (NUTS3 level) of Po river basin district (PRBD). Own elaboration.



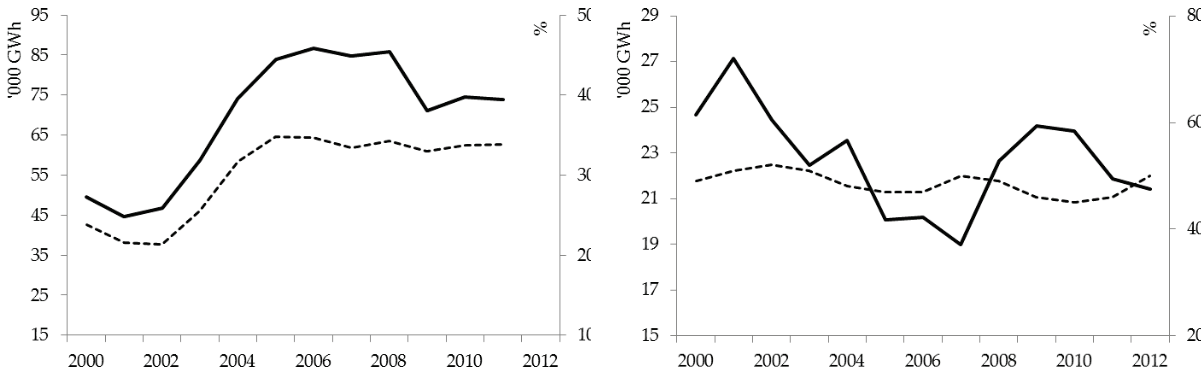
SM Figure 3: (*Left*) The electricity production across the Italian regions (*Right*) 2010 production in GWh; (*Left*) Relative changes 2010 to 2000 in per cent.



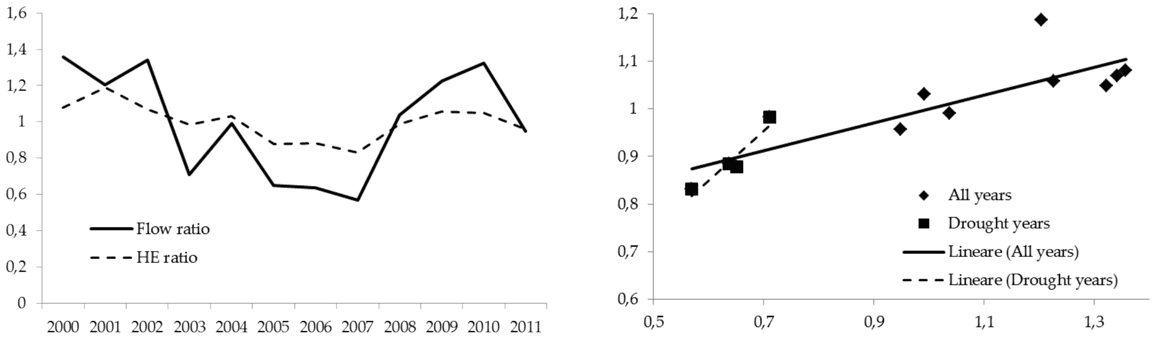
SM Figure 4: The electricity production across the Italian regions, in per cent of total national production.



SM Figure 5: Installed capacity (net) of the thermoelectric (*left*) and hydroelectric (right) power generation by the period of the installation. Own elaboration based on EAG data.



SM Figure 6: Thermo- (*left*) and hydroelectricity (*right*) generated in the PRBD (bold line) and the PRBD share in national production (dashed line). Own elaboration based on the Terna and AEG data.



SM Figure 7: (*Left*) Flow and hydroelectricity (HE) ratios to average (2000-2012) values over the period 2000-2012, (*Right*) Scatterplot of flow (x-axis) and HE ratios (y-axis) over the same period, with separate trend lines for the drought years 2003, 2005-07 (dashed) and the whole period.

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