VOL. 10, NO. 15, AUGUST 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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FLUCTUATION ANALYSIS OF CLIMATE-RELATED ENERGIES IN EUROPE

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ABSTRACT

European countries have a target to reduce the used of coal and fossil fuel and substitute them with renewable energy. Solar power, hydropower, and wind power are the most popular energies, but these power generations fluctuate based on weather variables. High dependence to weather also applied for energy demand. These climate dependencies (e.g. seasonality and intermittency) makes the integration of climate related energies into the conventional energy system potentially difficult. In this research, we assess the fluctuations of the energy production potential for different climate related energy sources. The analysis is done for 12 regions among Europe from long chronological times series of data obtained for 1980 to 2012 (33 years). The seasonal pattern of energy production is highly region dependent: solar power production are different between northern and southern areas due to differences in temperature and solar radiance cycles, hydropower production are different between northern-eastern and western areas due to precipitation patterns and snow dynamic, wind power production patterns differ between oceanic and continental areas based on the difference of wind speed, and the fluctuation of energy demand is different between northern and southern areas following the differences in heating and cooling needs especially for households. Cofluctuations between energy sources are finally explored suggesting the interest of mixes for a better integration of these energy sources.

Keywords: energy generation, fluctuation, weather variable.

INTRODUCTION

Renewable resources which can be used for energy production are solar system, biomass heating system, wind-powered system, geothermal heating system, and hydropower. Among these sources, the most popular are wind power, solar power, and hydropower (HP) because the potential of these sources is available almost everywhere, when not all countries have biomass or potential wood, geothermal potential, and sea source. These “Climate-related energies” (which will be noted as CRE) fluctuate following their driving hydro-meteorological variables such as precipitation, temperature, solar radiation, and wind speed (de Boer & Bressers, 2013).

Hydropower (HP) depends on precipitation and river flow. It has been developed all around the world using milling and pumping since 1700s (Kumar *et al.* 2011). There are three types of HP plant; Run-of-the river (RoR), Reservoir, and Pump-storage (Table-1). RoR is a HP system which cannot be scheduled because there is little or no storage system. Reservoir systems use dams for storing large quantity of water which can be used when the available resource is not sufficient. It can either be used for balancing other intermittent production such as solar and wind power or for other purposes such as fresh water and irrigation supplies, tourism, and ecological services. It also allows to increase the height of water drop and discharge for generating the transport of energy (International Renewable Energy Agency, 2012). Pump-storage, on the other hand, uses the electric pump to transfer water from the river or reservoir into the pumped storage plant (de Boer & Bressers, 2013). Small hydropower can produce 62 EJ/year (Moriarty & Honnery, 2012)

Solar system is divided into Photovoltaic panels (PV) and Concentrating Solar Power (CSP). The difference is the equipment used for converting solar radiation into the power. PV can directly convert the radiation into electricity using cell of semiconductor material. While CSP concentrates sun radiation to thermal energy within thin pipe, flat mirrors, or disks. This thermal energy will heat the fluid on the pipe of heat transfer fluids and produce mechanical energy for generating Solar Thermal Electricity (STE) (Ralph E.H *et al.* 2007). Since 2008, PV is becoming the most used (it has increased by more than 70%) because its manufacturing and maintenance cost can be decreased by 60% ($0.7/Watt-peak) and it can produce 25% of the current global consumption (4 TW/year) (Grossmann *et al.* 2013).

Wind power system converts the energy by employing the wind to drive wind turbine. This technology is suitable for a region which has large open-area because it needs more space for building wind farm (contained of some windmills) or for a region in coastal area which can develop offshore wind turbines. Moriarty & Honnery (2012) and Ralph E.H *et al.* 2007 have showed that wind power technology can take a large share in the different energy resources by displacing around 18% of fossil fuel consumption and around 11% of natural gas consumption.

VOL. 10, NO. 15, AUGUST 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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In European hydropower systems, a seasonal jump is often observed with potentially long lasting low flow periods, in summer (southern countries) or in winter (northern country). According to Hannaford *et al.* 2011, summer period when the most severe drought event can lead the lowest level of water resource for hydropower and can decrease the power product especially in southern areas.

On the other hand, solar heating system of PV or CSP depends on the duration of sun in daytime. The energy production of these technologies will decrease by 50% from summer to winter when the sunshine is shorter. The variability of energy from solar system also depends on the daily fluctuation of radiation. During cloudy days, the amount of energy production can decrease by around 1.5% per day (Kothe *et al.* 2013). If each country could use 27% of solar system as its energy source, then this technology will be able to supply nearly 80% of global energy demand by the end of 2050 (Grossmann *et al.* 2013).

In some locations, the amount of wind power in summer can be 50% higher in the winter. On spatial point of view, the largest difference of energy production usually also happens between coastal and continental areas. The highest wind speed are observed in near-coastal area (such as UK and Norway which also have the largest load factor of wind in winter) (Nawri *et al.* 2014). Wind speed is the main driving variable of wind power. It exists other as humidity, temperature but their effecet are much more slight. Then, technical factor as the size of the turbine controls the maximum power (nominal power) which can be generated. Usually, a windmill needs at least 3 m/s of wind speed to run its turbine, but when the storm comes (which has strong wind gust), turbines must be shut down and the total energy production in a wind farm decrease.

The fluctuation of energy demand is also happening in seasonal and diurnal scale. In diurnal scale, the highest energy demand for electricity occurs during work time (9 AM until 4 PM) and it is higher in winter than in summer for seasonal scale in European countries (ENTSOE, 2013). In addition, the electricity demand also depends on climate (based on seasonal changes such as winter and summer) and socioeconomic factor. In climate case, it is related to the used of electric heating and cooling while for the socioeconomic factor, it is more prompted primarily by the electricity price and income (Romero-Jordán *et al.* 2014).

CREs production and energy demand highly depended on the fluctuation of climate variables. This problem causes the integration of CREs in the conventional energy system quite difficult. Because of that, the aim of this paper is to gice an overview of the different regimes of CREs and energy demand patterns across Europe and to give some elements on the temporal inadequation between each energy resource and the demand.

DATA PREPARATION

Our study focuses on 12 regions spread all across the continent with different climate going from polar to Mediterannean areas (Figure-1). They belong to eleven countries namely Norway, Finland, Germany, Spain (Andalucia and Galicia), Greece, Italy, Tunisia, France, UK, Romania and Belarus. The analysis is based on energy production and energy demand data obtained at a daily time step from surface meteorological variables available for 1980 to 2012 (33 years).

The conversion of climate data to energy production and demand are obtained from their simple models assuming that they have the same type and level of equipment every where in Europe.

Figure-1. Study area.

Solar power generation

Solar heating system in this study is Photovoltaic panel (PV) and the input data for calculating solar power generation using equation (1) are solar radiation and temperature (Perpiñan *et al*, 2007). Temperature data come from ECAD weather analysis for European domain (Haylock *et al.* 2008) and solar irradiation data are pseudo observations obtained with the Weather Research and Forecasting model (WRF) from ERA-Interim atmospheric reanalyses (Vautard *et al.* 2014). The amount of solar radiance is the main factor of solar power generation, but cell and ambient temperature is also affecting this production (high temperature reduce the efficiency of solar cells).

$$P_{DC}(t) = \left(I_{eff}(t) A_g \{ \eta_{g,STC} [1 - \mu (T_a(t) - T_{c,STC})] \} + I_{eff}(t)^2 A_g \{ -\mu_{g,STC} \mu C \} \right) \times \mu_{inv} \quad (1)$$

Where P_{DC} is delivered power, A_g is surface area of PV (m), I_{eff} is effective incident irradiance (Wm^{-2}), $\eta_{g,STC}$ is efficiency of generator when the current power is under standard test condition (STC), μ is temperature coefficient of solar cells, C is the parameter parameter determined using the Nominal Operation Cell Temperature method, T_a is ambient temperature, and $T_{C,STC}$ is cell temperature. Standard test condition means that the solar panels have been tested in the factory to deliver 1000 Wm^{-2} of radiance, and holding a 25°C cell temperature.

Hydropower generation

Hydropower generation is assumed to be only produced with Run of River (RoR) power plant. Since RoR is the system without storage, thus, the available natural flow is directly converted into energy. Runoff data comes from daily data of Global Runoff Data Center

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(GRDC, 1999). The power generation is a function of water flow in the plant (Singh and Chandra, 2010):

$$P(t) = \rho g H Q(t) \tag{2}$$

Where ρ is water density (1000 kgm^{-3}), g is gravity (ms^{-2}), H is water head, and Q is water flow (ms^{-3}). Water head was set to 1 because we focus only on energy production fluctuations. The water flow used by the plant is simply the river discharge bounded by Q_{min} and Q_{max} related to environmental flow requirement in the river and to the maximum flow capacity of the plant. In this study, Q_{min} and Q_{max} are defined as 10th and 80th percentile of the discharge in the whole time series.

Wind power generation

Wind power production is a function of wind speed v (ms^{-1}) at the turbine hub's height. In this study, the height, H (m), is defined as 70 m. In the following, 10 m wind speed data obtained from WRF simulations (WRF, Vautard *et al*., 2014) are converted into 70 m wind (Lu *et al*., 2009; Li *et al*., 2009).

$$v_{H_{70m}} = v_{H_{10m}} \left(\frac{H_{70m}}{H_{10m}} \right)^{\alpha} \tag{3}$$

Where v_{H70m} is the wind speed at 70 m altitude (ms^{-1}), H_{70m} is the height of the turbine (m), and α is air fraction index related to the site configuration (forestry, sea, or mountainous). To convert 3-hours mean wind speed into 3-hours mean wind power generation, we developed the functional of Figure-3 from a classical wind power curve proposed for instantaneous wind data (Richardson & McNerney, 1993) in Figure-2. This wind power curve distinguish three main stages. Above the cut-in threshold, wind power is almost a linear function of wind speed. Then, it is constant for a given range of wind speeds. Lastly, when the wind speed is too fast (e.g. because of storm), the work of turbine is cut-off for safety reasons.

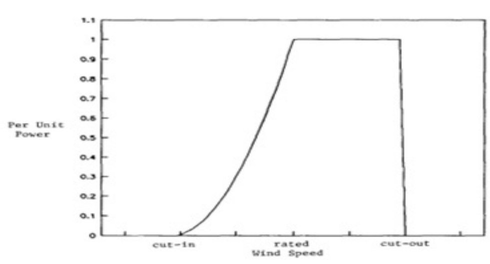

Figure-2. Wind turbine curve.

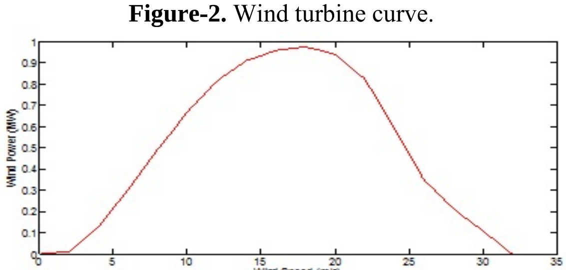

Figure-3. Wind power as a function of wind speed for three hourly mean data.

Energy demand modeling

Observed energy demand data have been provided by ENTSOE at the country scales for all regions (https://www.entsoe.eu/db-query/country-packages/production-consumption-exchange-package). No data is available before 2006. We reconstructed consumption data with a weather driven model calibrated on the period with observations. To better highlight the role of weather in the production/demand equilibrium, we assume that all other factors (e.g. population growth and socio-economic development) that are likely to influence the time evolution of the demand can be removed from the series. The standardization process has been done by removing holiday times, weekend days, population growth and socioeconomic events showing outlier conditions (i.e. economic crisis in 2008). For this, the demand data was divided by. The change of mean (shifted mean) in the data (e.g. trends and/or caused by the economic crisis on 2008) was then deleted.

Figure-4 illustrates the strong relationship between standardized energy demand and the air temperature in Europe.

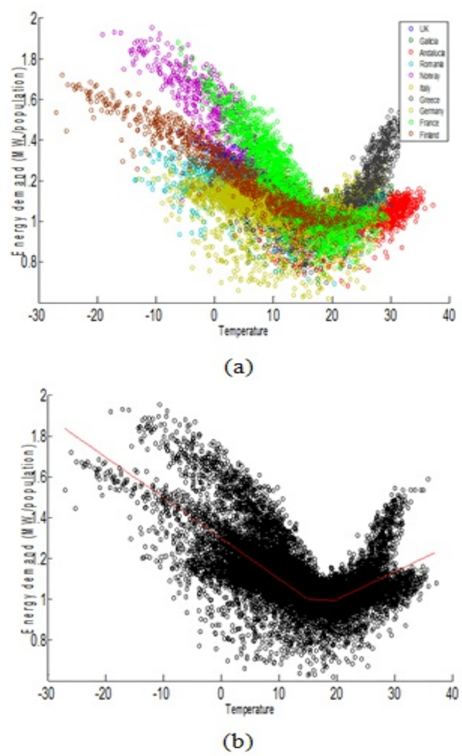

Figure-4. Plot of standardized energy demand over temperature in each country (standardization also includes a normalization for each region of the demand by the constant value of 15-20°C plateau) (a) and in all countries as one time series (b).

The energy consumption goes down from negative temperature until it reaches its minimum and a plateau when the temperature is about below 15°C and up

 ISSN 1819-6608

ARPN Journal of Engineering and Applied Sciences

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to 20°C. Then the demand increases again when the temperature is getting warmer. We fit on the corrected energy demand data a piecewise linear function between energy demand and temperature. According to Figure-4 (a), energy demand in all countries is approximately constant between 15-20°C.

Based on Figure-4 (b), a single energy demand model has been generated using the average of 12 regional models rather than estimating its parameters from the global European dataset (4) for two reasons: First, the sensitivity to temperature in each country is different. For example, in France the slope is very steep while it is much more gentle in Italy. This case can illustrate the different types of electricity uses in Europe: the higher the slope, the higher the sensitivity of consumed electricity to temperature (higher demand for heating and cooling systems). The second reason is that although we have standardized them, the lengths of the time series in all countries are different. Time series in France, Germany, Greece, Spain, and Italy begin on January 1st 2006, whereas time series of Finland, Norway, and UK begin in 2010. Averaging the different individual models allows not to give too much weight to regions with more data. The final model is defined as following:

$$d(t) = \begin{cases} -0.02T(t) + 1.31 & T < 15°C \\ 1 & 15°C \le T \le 20°C \\ 0.01T(t) + 0.79 & T > 20°C \end{cases} \quad (4)$$

Where d is energy demand and T is temperature. Daily demand data in the following are obtained from daily temperature by this equations (simulated energy demand).

ANALYSIS FRAMEWORK

This section describes how the fluctuation analysis have been done. Statistical analysis of energy production or demand consists for each variable of mean interannual daily cycles. We next discuss correlation coefficient between series obtained for different power sources or sources and demand.

Figure-5 shows for all regions the mean interannual cycle for each variable (one variable in each box, empty boxes correspond to countries with no data - hydropower for Spain, Italy, Tunisia, and Greece). The interannual cycle is computed on a calendar basis by taking the average of all the 1st of January from 33 years dataset, all 2nd January, etc. In addition, the 5th and 95th percentile of daily values for each calendar day is also presented.

RESULTS AND DISCUSSIONS

From interannual cycle, we can identify that wind power has a large daily variability and that its seasonality is higher in Western Europe, for regions which are close to Atlantic Ocean. Hydropower also exhibits a seasonality but different from one region to another. Maximum production is reached in spring for northern and it peaks in winter elsewhere, but with a high inter-annual variability. Sun power has a strong seasonality due to the fluctuation in duration of sunshine. This seasonality has been proven by basic statistic in Table-1 which shows that the mean and the variance of data in solar generation is the highest. In southern areas, solar production is higher compared to the other regions but this is not the same case in wind power, hydropower, and energy demand (see mean value in Table-1). Data variation in all observed data can be analyzed also by variance in Table-1. Based on the variance of that table, the range of wind power data is large in a whole time series. There is no strong seasonality in wind power. On the other hand, the seasonality in hydropower is not as strong as solar power. Hydropower in Finland, Norway, Belarus, and Romania increases at the beginning of spring because of snow melt and it decreases when snow accumulates in the beginning of winter. The other considered regions have rainfall driven hydrological regimes. The temporal pattern of hydropower thus follows the seasonality of precipitation (and also evapotranspiration along temperatures). In France, Germany, and UK energy decreases in summer and increase again in the beginning of fall. There are thus two main types of hydropower production regimes, depending on the importance of the snow dynamic in the area.

Interannual cycles show similar shapes in some countries. Based on patterns obtained for power sources, different groups of countries appear relative for instance to Nordic (Finland, Norway, and Belarus), Oceanic (France, Germany, Romania, and UK), and Mediterranean regions (Greece, Spain, Italy, and Tunisia). Similarly, the shape of energy demand is different in southern and northern area. In southern countries such as Greece and Italy, the energy demand is higher in summer because people need it for turning on the cooling system, but for countries in north of Europe such as Norway and Finland, the energy demand is higher in winter because of their heating system.

For each country, the comparison of the four climate related variables can also be done by the basic statistic including mean and variance (Table-1).

Table-1. Basic statistics for all observed data in each country.

Wind	BR	FIN	FR	GER	GR	IT	NO	RO	AN	GA	TU	UK
Avg	6.50	4.98	7.04	7.50	7.17	7.25	10.84	5.38	5.86	5.91	9.16	9.71
Var	15.88	11.30	20.27	18.77	21.72	17.68	35.76	12.89	14.11	14.15	22.87	29.36
Solar	BR	FIN	FR	GER	GR	IT	NO	RO	AND	GAL	TU	UK
Avg	120.9	96.7	134.6	124.7	159.6	143.6	99.77	143.8	165.1	142.0	168.6	109.8
Var	5450	6146	4159	4899	3199	3497	5926	4057	2651	4038	1885	4985
HEP	BR	FIN	FR	GER	GR	IT	NO	RO	AND	GAL	TU	UK
Avg	10.86	12.99	15.18	12.84	-	-	15.23	12.40	-	-	-	14.55
Var	100.7	126.3	188.4	149.2	-	-	150.8	117.1	-	-	-	154.2
Demand	BR	FIN	FR	GER	GR	IT	NO	RO	AND	GAL	TU	UK
Avg	1.17	1.23	1.08	1.12	1.07	1.08	1.19	1.13	1.05	1.05	1.04	1.04
Var	0.03	0.04	0.01	0.01	0.00	0.01	0.02	0.02	0.00	0.00	0.00	0.00

Among these powers sources, the correlation of powers and demand among countries using normalized data where the mean is zero and standard deviation is one (Table 3) has been calculated. In all tables, there are three different colors in each range:

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a. Correlation coefficients > 0.3 (yellow)
b. 0.3 ≤ correlation coefficients ≤ -0.3 (no color)
c. Correlation coefficients < -0.3 (orange)

Applying these colors to those countries will not only give the information about which correlation is lower than 0.6 (the threshold chosen to differentiate high and low correlations), but also inform us on which countries have the highest correlation coefficient.

At daily time step, the correlation between solar power time series obtained for the different regions is high whatever the couple considered and very similar from one group of regions to the other ranging from 0.79 to 0.88. For wind power, the highest correlation is between Galicia and France (0.50). In some cases, values are close to zero meaning no correlation between these regions (Tunisia/Norway, Tunisia/Finland, Tunisia/Galicia, also Romania/Finland). For hydropower, the highest correlation is between France and UK (0.62) and the lowest is in France and Norway (-0.29). Non-negligible negative correlation values illustrate that power generation in a country is higher when the other one is lower. Correlation coefficients in energy demand also show that Greece and Finland has the lowest correlation (-0.07) and the highest is between Finland and Norway (0.89). Correlation coefficients between times series of energy demand are more variable than correlation coefficients between times series of power production. These correlation coefficients show that countries of the Mediterranean area has different pattern of CREs for producing energy.

Table-2. Correlation coefficient of energy powers and demand in normalized values.

SOLAR												
	NO	FIN	UK	GER	BR	FR	RO	SPG	SPA	IT	GR	TU
NO	1.00	0.88	0.84	0.84	0.87	0.82	0.84	0.79	0.85	0.82	0.84	0.87
FIN		1.00	0.84	0.85	0.87	0.83	0.84	0.80	0.84	0.82	0.83	0.86
UK			1.00	0.83	0.85	0.83	0.83	0.80	0.82	0.80	0.83	0.84
GER				1.00	0.87	0.86	0.86	0.79	0.82	0.86	0.83	0.84
BR					1.00	0.85	0.88	0.81	0.85	0.83	0.85	0.87
FR						1.00	0.84	0.84	0.82	0.83	0.83	0.84
RO							1.00	0.81	0.85	0.83	0.86	0.86
SPG								1.00	0.84	0.80	0.81	0.81
SPA									1.00	0.82	0.85	0.87
IT										1.00	0.82	0.84
GR											1.00	0.85
TU												1.00
WIND												
	NO	FIN	UK	GER	BR	FR	RO	SPG	SPA	IT	GR	TU
NO	1.00	0.32	0.21	0.17	0.10	0.13	0.03	0.07	0.06	0.11	0.10	0.00
FIN		1.00	0.12	0.07	0.16	0.07	0.00	0.02	0.02	0.02	0.09	0.00
UK			1.00	0.04	0.10	0.24	0.04	0.11	-0.05	0.10	0.41	0.03
GER				1.00	0.04	0.07	0.26	0.04	0.10	0.25	0.08	0.22
BR					1.00	0.07	0.30	0.03	0.04	0.09	0.21	-0.01
FR						1.00	0.07	0.50	0.13	0.18	0.38	0.01
RO							1.00	0.07	0.08	0.32	0.23	0.08
SPG								1.00	0.44	0.09	0.13	0.00
SPA									1.00	0.09	-0.04	0.04
IT										1.00	0.47	0.34
GR											1.00	0.05
TU												1.00
HYDRO												
	NO	FIN	UK	GER	BR	FR	RO					
NO	1.00	0.37	-0.28	-0.25	-0.06	-0.29	0.08					
FIN		1.00	0.19	0.23	0.34	0.20	0.17					
UK			1.00	0.50	0.27	0.62	0.02					
GER				1.00	0.41	0.60	0.26					
BR					1.00	0.25	0.28					
FR						1.00	0.11					
RO							1.00					
ENERGY DEMAND												
	NO	FIN	UK	GER	BR	FR	RO	SPG	SPA	IT	GR	TU
NO	1.00	0.89	0.85	0.79	0.81	0.70	0.70	0.53	-0.03	0.72	0.37	-0.24
FIN		1.00	0.80	0.80	0.87	0.72	0.77	0.55	0.01	0.75	0.46	-0.17
UK			1.00	0.87	0.80	0.82	0.74	0.62	0.03	0.79	0.43	-0.18
GER				1.00	0.88	0.89	0.85	0.66	0.17	0.89	0.57	-0.03
BR					1.00	0.77	0.90	0.60	0.09	0.82	0.60	-0.07
FR						1.00	0.75	0.78	0.31	0.88	0.53	0.06
RO							1.00	0.60	0.17	0.84	0.77	0.05
SPG								1.00	0.58	0.70	0.48	0.16
SPA									1.00	0.31	0.34	0.59
IT										1.00	0.67	0.15
GR											1.00	0.40
TU												1.00

Besides computing correlations between countries, correlations between powers and demand in each country have been done. This computation cannot be done between all powers and demand because the length of the time series is not balance (reconstructed time series of river discharges could be simulated with hydrological simulations, but such a model was unfortunately not available for this region). It is due to time series of hydropower ending in 2004, and time series of demand starting in 2006. Because of that, two groups of correlations have been done: 1) Solar power versus wind power versus hydropower from 1980 until 2004 (Table-3), 2) solar power versus wind power versus simulated energy demand from 1980 until 2012 (Table-4). According to those coefficients, solar power almost has negative correlation with all the other power sources in every country which means that when the solar power increase, the others go down. The same comment can be made between solar power and demand.

Table-3. Correlation coefficients between all energy power.

BI	S	W	H	FIN	S	W	H	FR	S	W	H
S	1.00	-0.18	-0.07	S	1.00	-0.19	-0.02	S	1.00	-0.37	-0.37
W		1.00	0.10	W		1.00	0.10	W		1.00	0.31
H			1.00	H			1.00	H			1.00
GER	S	W	H	NO	S	W	H	RO	S	W	H
S	1.00	-0.35	-0.23	S	1.00	-0.41	0.39	S	1.00	-0.22	0.21
W		1.00	0.22	W		1.00	-0.07	W		1.00	0.07
H			1.00	H			1.00	H			1.00
				UK	S	W	H				
				S	1.00	-0.30	-0.42				
				W		1.00	0.40				
				H			1.00				

Table-4. Correlation coefficients between solar power, wind power, and simulated energy demand.

FIN	S	W	D	FR	S	W	D	GER	S	W	D
S	1.00	-0.19	-0.69	S	1.00	-0.37	-0.62	S	1.00	-0.35	-0.69
W		1.00	0.12	W		1.00	0.20	W		1.00	0.22
D			1.00	D			1.00	D			1.00
NO	S	W	D	RO	S	W	D	BR	S	W	D
S	1.00	-0.41	-0.63	S	1.00	-0.22	-0.72	S	1.00	-0.18	-0.73
W		1.00	0.31	W		1.00	0.14	W		1.00	0.09
D			1.00	D			1.00	D			1.00
				UK	S	W	D				
				S	1.00	-0.30	-0.65				
				W		1.00	0.21				
				D			1.00				

VOL. 10, NO. 15, AUGUST 2015 ISSN 1819-6608
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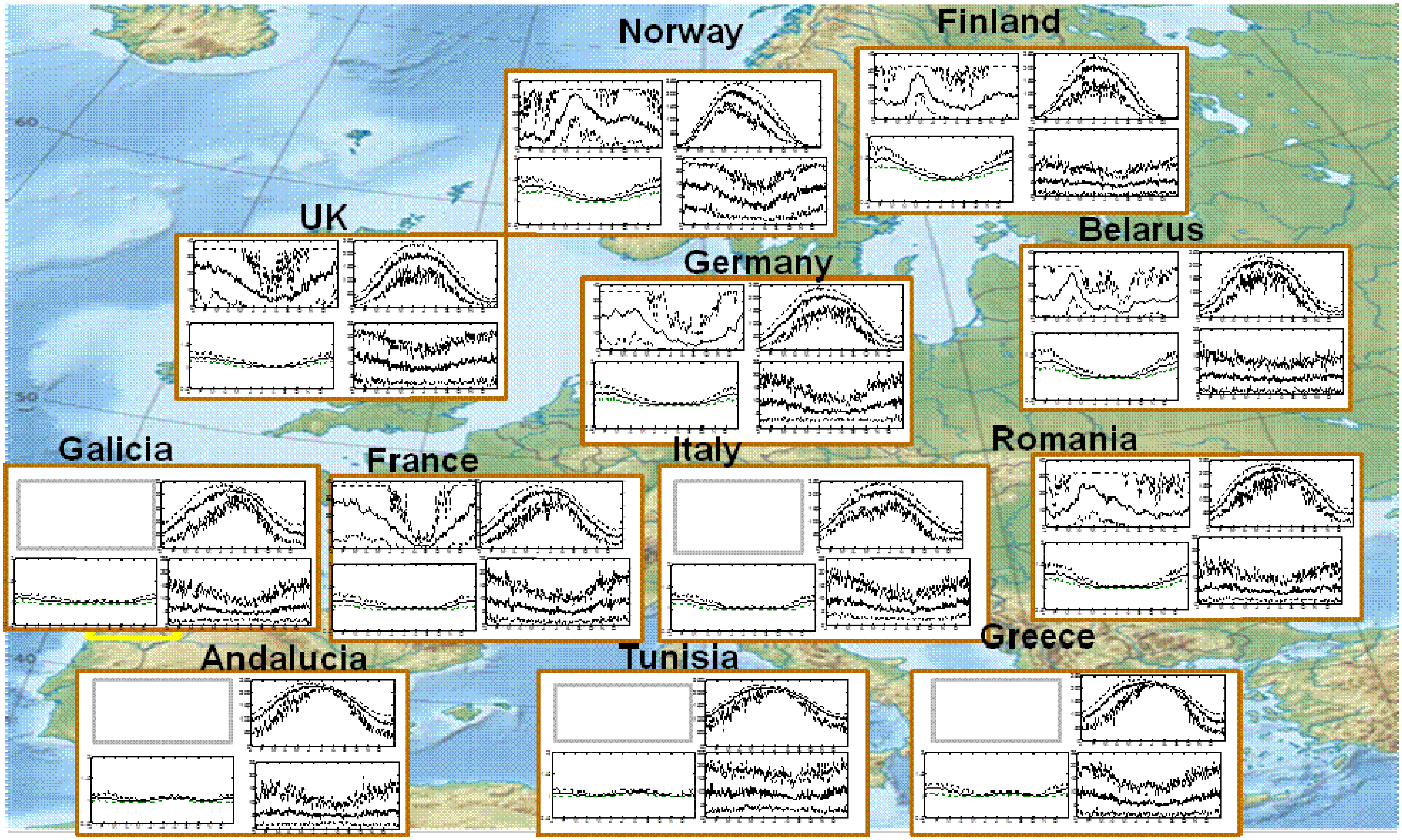

Figure 5 Daily observed average cycle of hydropower (below right), solar power (below left), wind power (top right), and demand (top left). The black line is the average data and the dashed lines are 5th and 95th percentiles

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CONCLUSIONS

Based on the pattern of energy production in interannual cycle, solar power production in northern and southern areas are different due to the fluctuation of temperature and solar radiance in summer and winter. Besides, hydropower production are different between northern-eastern and western areas. In northern and eastern countries (Finland, Norway, Belarus, and Romania) are affected by snow accumulation, but hydropower in western countries (France, Germany, and UK) are affected by precipitation. The fluctuation of energy demand in northern and southern areas is also different due to their energy consumption for either heating or air conditioning.

The analysis of their fluctuation have been done also using correlation coefficients. The result shows that solar power generation almost always have negative correlation with other resources indicating that when solar power production increases, the others decrease. The globaly low correlation results obtained for the other variables also suggest the high potential of mixes of different energy sources from different regions to increase the penetration rate of CREs in the conventional European energy system.

ACKNOWLEDGEMENTS

This paper is extracted from a master thesis done within the HydroHazard Master Program (http://www.hydrohasards.eu) which is a part of the FP7 project COMPLEX (Knowledge based climate mitigation systems for a low carbon economy; http://www.complex.ac.uk/).

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