Scenarios for wind-solar energy mix in Italy from regional climate simulations

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Intermittency and diversification (1/2)

- In the perspective of limited amount of fossil fuels, climate change and energy security concerns, renewable energies will inevitably play a major role
- Non-hydropower renewable sources are the fastest-growing energy sources for new generation capacity: their share is expected to grow from 7% of total world generation in 2015 to 15% in 2040, with more than half of this growth coming from the wind power (IEA, 2017)
- Technological and spatial diversification are possible strategies to overcome the problem of intermittency:
  - In Europe, wind and solar-generated electricity have negatively correlated seasonal cycles
  - Spatial diversification is applicable at large scale (Heide et al., 2010; Widen et al., 2011; Tsuchiya et al., 2012)

Intermittency and diversification (2/2)

- Technological and geographical optimization of renewable energy systems within a multi-objective framework has been discussed in existing literature at continent and country scales
- Some of these studies apply Markowitz Mean-Variance Portfolio theory to optimize the full repowering of existing power plants
- Repowering consists in fully decommissioning current renewable energy capacity and re-allocating this capacity according to specific objectives (Del Río et al., 2011).

Paper's novelty

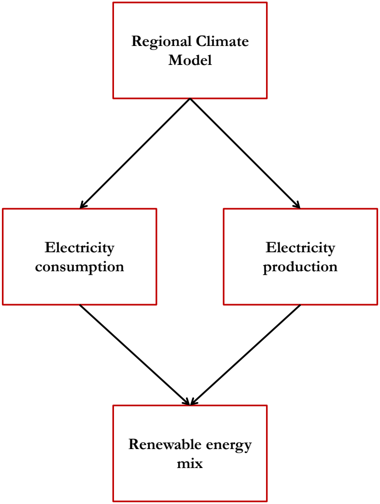
- We go beyond this approach, combining:
  - regional climate simulations
  - network physical constraints
  - profitability goals
- We use the Italian Power Market as a case study to compare the existing generation capacities with those of the optimized scenario by allowing full decommissioning of currently installed RES power plants
- Italy offers an interesting case study of a market with high renewable penetration and a zonal organization

The Italian Power Market

- Italy has reached its quota of 17% of renewables in final energy consumption in 2014 (6 years ahead of the 2020 horizon fixed in the 2009 Climate Package)

- 6 inter-connected regions with their own generation mix
- transmission constraints between zones
- inter-zonal capacities depend on historical and geographical reasons

Data and methodology



Data:

- Climatic dataset
  - Weather and Forecast Research (WRF) model
  - Numerical integration: 20km resolution
  - Period 1989-2012
- Electrical dataset
  - GME: Hourly offers/bids in the day-ahead market (2010 - 2014)
  - GSE: Regional transmission and RES capacities

Methodology

- Optimization of solar and wind production according to Markowitz's portfolio theory

Electricity production model

Wind Production

- Simulated horizontal wind speed interpolated at hub height (100m)
- Electrical production from wind speed computed with a transfer function using the power curve
- The production is scaled to the current region's load factor and aggregated on daily basis

PV Production

- Solar radiation partitioned into direct and diffuse components
- Radiation computed assuming a 25° plan with a south orientation
- Conversion of solar radiation accounts for the air temperature, clearness index and several load loss factors
- The production is scaled to the current region's load factor and aggregated on daily basis

Hydro + Conventional Production

- Constant and set at 80% of the maximum electrical demand

Electricity consumption model (1/2)

- The demand is modeled using a truncated Fourier series either at country or regional scale
- Annual and weekly cycles are modeled as a sum of sines and cosines modulated by calendar and weather data from the HyMeX/MED-CORDEX simulation:

$$
\begin{aligned}
D(t) = \quad & A_1(t)\sin\left(w(t)\frac{2\pi}{53}\right) + A_2(t)\cos\left(w(t)\frac{2\pi}{53}\right) \\
& + A_3(t)\sin\left(w(t)\frac{4\pi}{53}\right) + A_5(t)\sin\left(w(t)\frac{10\pi}{53}\right) \\
& + A_6(t)\cos\left(w(t)\frac{10\pi}{53}\right) + B
\end{aligned}
$$

where:

- $D(t)$ is the daily simulated consumption in MWh
- $w(t)$ is the week of the year (from 1 to 52 or 53)

Electricity consumption model (2/2)

- Coefficients $A_i(t)$, with i the region number ranging from 1 to 6, are estimated by ordinary least squares using the following model:

$$
\begin{aligned}
A_x(t) = \quad & we(t)\left(a_{i,0} + a_{i,1}T_{max}(t) + a_{i,2}fdd(t)\right) \\
& + sat(t)\left(b_{i,0} + b_{i,1}T_{max}(t) + b_{i,2}fdd(t)\right) \\
& + wk(t)\left(c_{i,0} + c_{i,1}T_{max}(t) + c_{i,2}fdd(t)\right)
\end{aligned}
$$

where:

- $T_{max}(t)$ is the daily maximum temperature
- $fdd(t)$ is the sum of degrees below 0^oC of the daily minimum temperature over the last three days
- wk, sat, we are dummies for working days, Saturdays, national holidays and Sundays respectively

- The performance of the model (simulated vs actual consumption during the 2010-2012 period):

Timescale	RMSE (%/MWh)	NRMSE (%)	R^2	$\sqrt{R^2}$
Weekly	918	9.33	0.73	0.86
Daily	1504	9.26	0.80	0.89

Mean-variance analysis (1/2)

- Geographical and technological diversification of RES power plants is based on Markowitz's mean-variance portfolio theory

- The mean-variance analysis refers to the process of finding optimal spatial and technological distributions of renewable energy production (renewable portfolios) achieving a trade-off between the average penetration rate (mean) and the variance of renewable penetration

- Minimizing the variance corresponds to maximizing the diversification of the renewable configuration, which in turn lowers the variability of renewable energy penetration and improves the flexibility of the system and its resistance to shocks

- The trade-off between penetration rate and risk is accomplished in two ways:
  - by finding the portfolio with the lowest variance given a desired mean value
  - by finding the portfolio with the highest mean given the level of variance

Mean-variance analysis (1/2)

- Each renewable portfolio can be represented in a mean-variance chart together with the efficient frontier, the set of optimal portfolios
- The frontier is determined using a multi-objective programming technique, namely the ϵ-constraint approach (see Steuer, 1986)
- The target is the renewable penetration rate in Italian electrical mix, ranging from 0 to 100%
- Three approaches have been used:
  - Global approach
  - Regional approach
  - Profitability approach

Global approach (GLO)

- Hypothesis: the electricity is immediately available to meet the demand, regardless of geographical location
- The mathematical formulation is:

$$\min \left| \sum_{i=1}^{N} \omega_i \mu_i - \mu_{Target} \right| \quad \text{and} \quad \min \sum_{i=1}^{N} \sum_{j=1}^{N} \omega_i \omega_i \sigma_{ij} \tag{1}$$

$$\sum_{i=1}^{N} \omega_i = \overline{\omega} \quad \text{and} \quad 0 \leq \omega_i \leq \overline{\omega} \tag{2}$$

where:

- N, the Italian regions (6) times the number of technologies (2, PV and wind)
- ω_i is the installed capacity in MW
- μ_i is the average RES penetration rate for a 1 MW plant for each region
- μ_{Target} is the overall target penetration rate
- $\overline{\omega}$ is the upper bound of the installed capacity at country scale (23.2 GW)
- σ_{ij} is the covariance between pairs of regions and renewable energies

Regional approach (REG)

- Hypothesis: a notion of electrical network is included
- The regional production must first be used to supply regional consumption:

$$\mu_i = \frac{1}{T} \sum_{t=1}^{T} \frac{P_i(t)}{D_i(t)} \tag{3}$$

where:

  - P_i is the RES production
  - D_i is the regional electrical demand
  - T is one year

- If the production is larger than demand, electricity can be exported to the extent of the regional transmission capacity
- In this case, we add the following constraint to the formulation (1)-(2):

$$\mu_i \omega_i \leq D_i(t) + T_i, \tag{4}$$

where T_i is the total incoming transmission capacity of i-th region

Profitability approach (ROE)

- Hypothesis: the profitability of portfolios is considered
- A third objective function minimizing the ratio between renewable cost and revenues is added:

$$\min \sum_{i=1}^{N} \omega_i (CAPEX_i + 24 \cdot OPEX_i - \mu_i \omega_i \cdot EPrice) \tag{5}$$

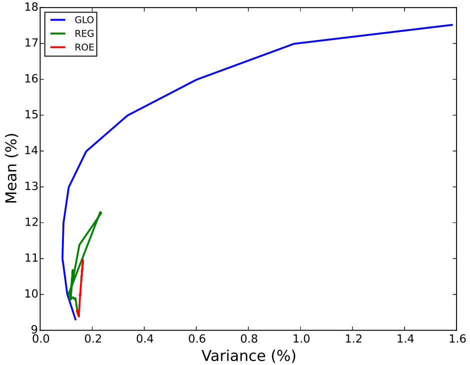
where

  - $CAPEX_i$, $OPEX_i$, and $EPrice$ are the capital and operating expense and electricity price

- In this study:
  - the CAPEX for PV and wind energy production is 879 k€/MW and 1279 k€/MW, respectively
  - the OPEX for PV and wind energy production is 31 k€/MW/yr and 42 k€/MW/yr, respectively
  - the electricity selling price is 172.153 €/MWh

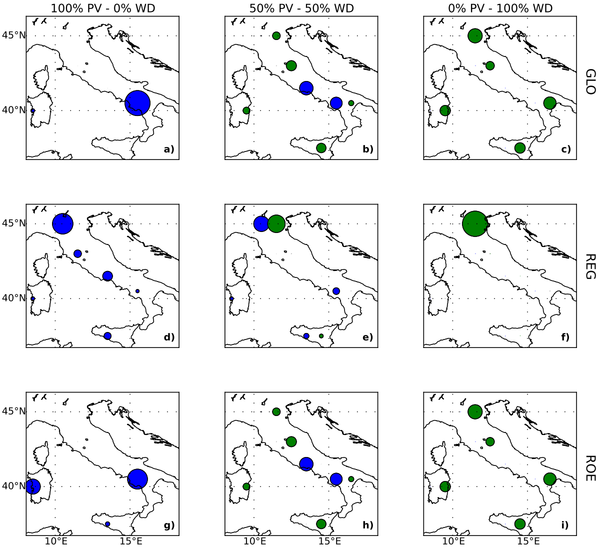
Efficient frontier

- Each point on the curve represents an optimal combination that maximizes the penetration given the risk (spatial variability)

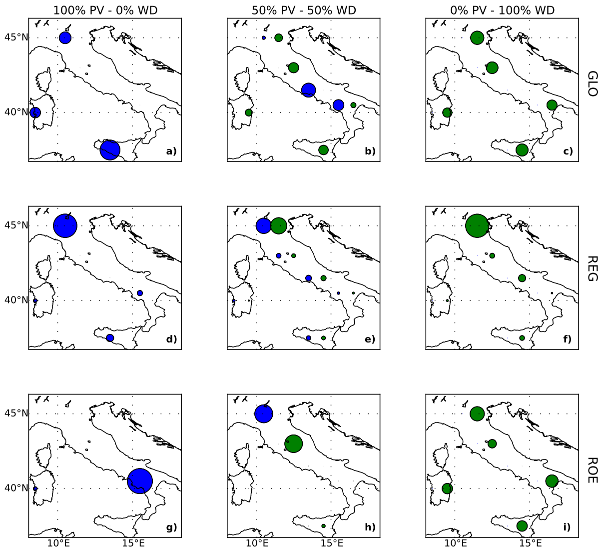


- Two scenarios:
  - Penetration scenario (max penetration - upper right dot)
  - Diversification scenario (min risk or max diversification - lower left dot)

Penetration scenario (PV, blue - Wind, green)



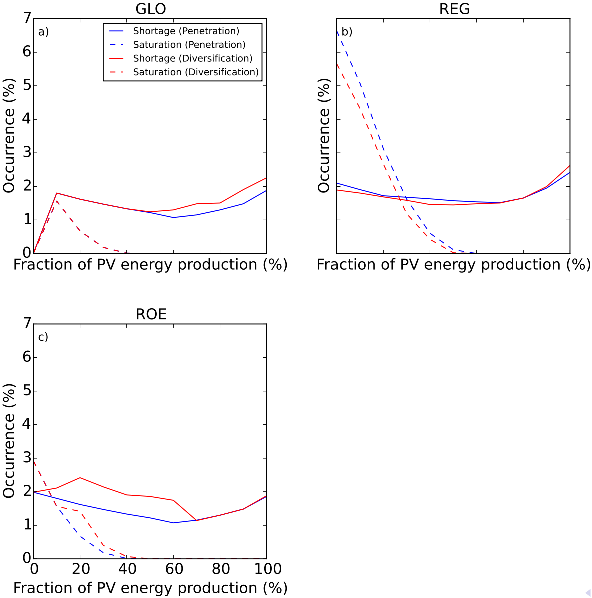
Diversification scenario (PV, blue - Wind, green)



Optimal energy mix (1/4)

- The optimal energy mix is inferred by minimizing the occurrence of two critical situations:
  - Shortage, or the energy “droughts”, corresponding to large cold or heat waves and low renewable energy production, especially from wind
  - Saturation of the network, when electricity production from RES exceeds the technical limit of renewable energy fraction in the energy mix (here set to 40%)

Optimal energy mix (2/4)



Occurrence of

- shortage (solid line)
- saturation (dashed line)

as a function of the fraction of PV production in the energy mix (PV and wind energy production) for

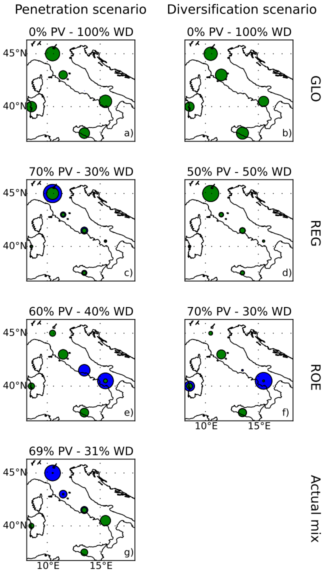
- the penetration (blue) scenario
- the diversification (red) scenario

Optimal energy mix (3/4)

- Minimizing the occurrence of both situations is equivalent to find the minimum of the sum of the two curves (the correlation is zero)

- The optimal energy mix is
  - GLO: 100% wind energy (for both penetration and diversification scenarios)
  - REG: 30%-70% PV/wind mix (penetration scenario) and 50%-50% (diversification scenario)
  - ROE: 40%-60% PV/wind mix (penetration scenario) and 30%-70% (diversification scenario)

Optimal energy mix (4/4)

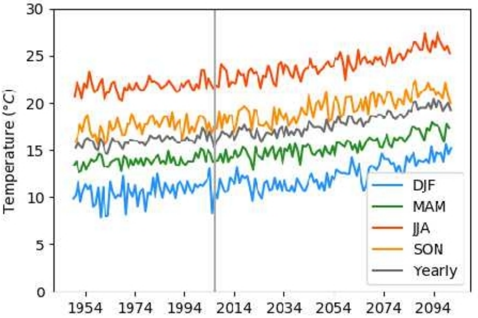


Conclusions

- The aim of this work is to develop a proof-of-concept of an integrated modeling framework dedicated to the elaboration of scenarios of renewable energy mix
- We derive different scenarios consisting in either maximizing renewable energy penetration or minimizing the risk by reducing the spatial variability of renewable energy penetration
- Different optimization strategies have been chosen to establish the energy mix scenarios: global, regional and financial
- Confrontation with the Italian actual energy mix shows that on average the actual and simulated energy mix profiles are similar with a 70% share of PV energy production and a 30% share of wind energy production
- However, differences in the spatial deployment of PV and wind energy technologies exist between the actual and simulated installed capacities
- The reasons are difficult to identify as the actual renewable energy capacity deployment did not follow an optimization elaborated at country scale, but relied on regional and national policies

The way forward

- Simulation of future climatic situations
- Significant trend in temperature impacting on:
  - energy demand
  - PV and wind energy



Thank you!