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Adaptation of the Italian electricity system to reduced water availability

WaterGAMS

Course of Energy and climate change modeling and scenarios

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Introduction

One of the many effects of Climate Change is the alteration of the water cycle. The Mediterranean area is projected to experience an increase in the duration and intensity of droughts[1]. As assessed by the IPCC AR6[2], hydroelectric and thermal power plants and the irrigation of bioenergy crops require large amounts of water.

Implementation and calibration of the model

The project is based on the OSeMOSYS model. It has been integrated with OSeMBE: the European scenario[3], which includes European countries as different regions. In this analysis, data about Italy was extracted and adapted to the OSeMOSYS GAMs language standard.

OSeMBE offers 15 time slices, composed of 5 seasons and 3 daily time periods (whose length varies depending on the season) which have been defined based on electricity demand, wind power and solar PV power production.
The time span considered for the analysis is 2015-2050, a crucial period to address the worsening effects of climate change. However, the data extends until 2060, to avoid the edge effect.

Electricity demand and production

Electricity demand is an exogenous parameter in OSeMOSYS, so it has been incorporated into the model through estimates and predictions: for the years 2015-2022, actual data was obtained from Terna reports[4]. To outline future electricity demand in Italy, the model uses projections provided by Terna based on the Fit-for-55 plan for 2030 and an increased electricity penetration by 2040, aiming for Net Zero emissions by 2050. These prospects fall within the range of scenarios proposed by the ENTSOE[5].
Electricity exports to other countries were excluded due to their little relevance. However, the import of electricity from neighbouring countries plays a crucial role in the Italian grid, accounting for an average of 13% of the domestic demand in recent years (with a range of [11%, 15%] since 2010). Consequently, the electricity demand has been multiplied by 0.87 to calculate the parameter *SpecifiedAnnualDemand*.

In a similar manner, the data for the capacity of power plants in *ResidualCapacity* was updated for the period 2015-2021 using real values from Terna and, to ensure an accurate technology mix for the initial 6 years, the *TotalMaxCapacity* paramater closely matches the real data. From 2022 to 2060, data for various technologies required adjustment, and multiple sources were considered for this purpose.

Policies

The analysis is set within the context of the European "Fit For 55". Italian policy makers set the carbon phase-out for 2025, therefore no investments in coal have been permitted. Moreover, limitations were put on natural gas and oil extraction according to IEA statistics. Projections from PNIEC[6] were also incorporated, setting minimum capacities for solar PV and for wind turbines to be installed by 2030. For geothermal energy, the *TotalMaxCapacity* was maintained at the 2021 value until 2030, and subsequently increased according to the expected availability of the resource. Hydropower capacity was given a minimal margin of increase by renovating existing plants. However, the construction of new hydroelectric power plants is constrained by limited adequate locations in the country.

The possibility of developing nuclear power plants from 2036 was also included in the model.

This time frame could be considered reasonable from a technical standpoint, although it may face challenges in terms of social consent. As a result, to observe potential differences, a scenario was created that excludes nuclear power.

By default, only pumped storage was included as a storage technology in the model. However, considering that batteries have been increasingly deployed in Italy, batteries were added as a new storage technology in the model.

Emissions

As expected by European legislation, the model imposes a CO2 emissions decline reaching net zero emissions by 2050. The pathway is set by the FF55 2030 agenda, requiring a 43% reduction in emissions compared to 2005 levels. The 2005 initial value consists of CO2eq emissions produced by the energy industry, which amounted to 161.3Mt[6]. The compliance to those goals has been obtained imposing a cap on CO2 emissions, as a simplified representation of the European ETS system, defining a smooth curve that includes past and future pinpoints.

In OSeMBE, CO2 emissions are attributed to the primary fossil fuel import or extraction, taking into account their potential emissions in the future. As a result, power plants that utilize carbon capture and storage (CCS) technology, which becomes available from 2030 onwards, have negative emissions levels (However, due to their high cost, they will not be utilized by the model).
Electricity produced from biofuel or biomass has been considered carbon neutral. Emissions resulting from waste-to-energy plants have been included (60 tCO2/PJ[7]) by analyzing the actual amount of CO2 released during the combustion of waste, excluding emissions derived from biogenic carbon, which would count as net zero.

Water consumption

Data on water consumption for power plants were gathered from literature and European inventories[8]. As the data were aggregated by fuel and type of cooling system, to avoid excessive complexity a weighted average was employed to determine a mean value for the various parameters of each technology. The same approach has been applied to biofuels, averaging on the most common energy crops cultivated in Italy. Consequently, specific values for water withdrawal and discharge were assigned to each power plant to accurately model water demand and usage within the system. Water consumption from fossil fuel extraction was also taken into consideration.

In the model, water unavailability affects both running water and precipitation reserves, while sea water remains a constant source for cooling purposes (the increase of seawater temperature has been deemed irrelevant for our purpose and time range).
For the purpose, new types of power plant that utilize sea water for cooling have been introduced as technologies in the model. Indeed, reflecting the current Italian energy landscape, all operational coal-fired power plants are situated along the coastline, together with existing examples of natural gas, oil, and waste-powered plants also operating in coastal regions. These technologies have higher costs due to increased investments and maintenance expenses associated with components exposed to saltwater.

In addition to the aforementioned uses, water is necessary in industrial, agricultural, and domestic sectors. In the event of water scarcity, priority is given to agricultural and domestic needs, by means of an annual water demand level.
All baseline data is taken from ISTAT reports, in particular household water demand depends on population decrease. Three potential scenarios have been outlined: the first is centered around reducing water network losses as per the PNRR, while the remaining two involve adjustments to achieve the average and optimal European levels of water efficiency, respectively[9]. Projections are given yearly, but the final demand has been split in different seasons through the *CapacityFactor* parameter, considering past trends.

Water availability

Water is made available to technologies that require it through the *RIVER* technology, whose

TotalAnnualMaxCapacity represents the annual availability of water for the Italian system.[10] To precisely depict the dynamic behavior of available freshwater capacity, the following equation was introduced:

$$\begin{aligned}\text{Capacity}(y+1) = \text{Capacity}(y) - \text{RiverUse}(y) \\ + \ \text{Precipitations}(y+1) - \ \text{EvaTrasp}(y+1)\end{aligned}$$

Such equation considers the precipitations within the year (included as exogenous source), the usage of water of the previous year and the factor of evapotranspiration given by Turc's equation, which establishes a relationship between temperature, precipiation and evaporation rates.

$$\text{EvaTrasp} = \begin{cases} \dfrac{\text{P}}{\sqrt{0.9 + \text{P}^2/\text{L}^2}} & \text{if } \text{P}^2/\text{L}^2 \geq 0.1 \\ \text{P} & \text{if } \text{P}^2/\text{L}^2 < 0.1 \end{cases}$$

$$\text{where } \text{L} = 300 + 025\text{T} + 0.05\text{T}^3$$

For what concerns water availability, a combination of groundwater resources data[11] and the Po river levels[12] was analyzed. The Po river, being the main river in Italy and situated in the area of high electricity production, was chosen as a reference for this assessment.
Projections regarding rainfall and mean temperature under different climate change scenarios (RCP2.6, RCP4.5 and RCP8.5) were taken from a study based on BIGBANG methodology[11]. Each scenario represents a distinct potential dynamic of the hydrological system, showing variations in temperature, which directly impacts evapotranspiration rates, in the levels of water availability and therefore in the water demands from the agricultural sector (higher in the more severe scenarios)[13].

These information have been considered and integrated into a statistical learning model, which has enabled detailed seasonal projections of future water availability. In particular, a SARIMA model was built by using historical data of the Po river levels (from 2008 to 2022) as training set and exploiting the strong correlation between water levels and the seasons. Indeed this model, extension of the more well-known ARMA model, is well-suited model for the analysis of periodic non-stationary time series and has been therefore used to predict water levels from 2023 to 2060.
The so obtained projections exhibit elastic curves which, after a proper rescaling, could effectively represent various phenomena connected to the cycle of water in Italy, including the behaviour under the three considered scenarios. To capture the inherent stochastic nature of real-world water systems and introduce variability, additional unpredictable noise was incorporated into the projections. The seasonal pattern has been introduced through the *CapacityFactor* parameter, which is adjusted to accurately represent the seasonal levels observed in the training set.

Results and Conclusions

Thanks to this model, it was possible to investigate Italy's ability to handle the hydrological crisis and the consequent damages.
Indeed, the model provides insights into the optimal mix of strategies that Italy can implement. Secondly, it allows for the exploration and comparison of the dynamics and policies needed to address different climate scenarios. This includes the utilization of storage technologies as compensation tools, the possible introduction of nuclear power in Italian energetic mix, the use of saltwater as an alternative source for cooling water, and the necessary financial investments needed to transition to a net-zero system and adapt to potential new environmental conditions.

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