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Multi-year storage or flexible imports for energy security under climate uncertainty?

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Mitigating climate change while supplying the power sector and electrifying heating, transport, and industry requires weather-dependent energy sources, like wind, solar, and hydro. Weather-dependent supply adds to the already weather-sensitive demand and challenges future energy systems. Over short periods, supply and demand mismatches are manageable thanks to reliable weather forecasts and technical solutions, like short-term storage, particularly batteries, demand-side flexibility, and power grids. However, the longer the mismatch prevails, the harder it becomes to manage. The lack of accurate long-term weather forecasts raises uncertainty, and, as a technical solution, only long-term storage or flexible imports remain due to the growing magnitude of the energy deficit.

Last winter, European power systems were already under stress when the wind generation was low, and cold temperatures induced high demand, causing a multi-year deficit, also referred to as Dunkelflaute [1]. In the future, the growth of renewables and electrification will aggravate the problem, extending the potential duration of the deficit from a few days to multiple months or years. In South America, such multi-year energy draughts are already occurring since energy systems heavily depend on hydropower. Below-average rainfall in the last years depleted reservoirs, resulting in a severe energy crisis and frequent blackouts [2].

Fig. 1 exemplifies the challenge of multi-year storage and draughts. Here, the system can manage the most extreme year since storage levels are sufficient to compensate for low wind supply and high heat demand during winter. The following two years are less extreme, at least if considered separately, but in conjunction, they cause a severe shortage. In summer, below-average surpluses from hydro and PV prevent refilling the storage, and, as a result, the storage runs dry after two winters with adverse but not extreme weather.

Hedging against these fluctuations is a stochastic problem since the deficits during winter are uncertain, just like the available surplus for filling the storage during summer. Reliable weather forecasts are not possible months or years in advance. In addition, it is not a storage but a system problem since security depends on the distribution of deficits and surpluses. For instance, more PV will reduce year-to-year variations and uncertainty but increase seasonal imbalances since generation in winter is low. In the heat sector, electrification reduces total demand but increases uncertainty since winter deficits become more temperature-sensitive. Accordingly, in the example, the shortage could be prevented in three ways: extend the storage and avoid spillage, reduce the deficits during winter, or increase the surplus in summer.

In this work, we investigate how net-zero systems can be reliable and counter the risk of climate uncertainty, including multi-year draughts. As a first option, we consider multi-year storage with hydro reservoirs and hydrogen, methane, or methanol storage. Available sources for these fuels are domestic production and import contracts with limited flexibility. As an equivalent substitute, we consider decreasing climate vulnerability by adapting the composition of supply and demand. This adaptation includes the continued use of fossil fuels during deficit periods and offsetting emissions with direct air capture during surplus periods, as long as the expected greenhouse gas emissions are zero.

The analysis extends an existing energy planning model of the European system to a stochastic optimization under climate uncertainty with limited foresight [3]. We introduce a robust formulation for multi-year storage that implicitly considers thousands of weather years but keeps the problem size manageable. Since the resulting optimization problem remains massive, we solve it with a Benders decomposition algorithm refined for this problem.

As a data source, we extend an existing climate data set covering 35 years of PV, wind, and hydro generation with consistent heat demand and heat pump efficiency data [4]. Based on an autocorrelation analysis, we assume weather conditions in different months are stochastically independent. Therefore, we select a subset of representative months from the sample with an optimization-based clustering algorithm. Since the stochastic planning model implicitly considers all combinations of the representative months, a subsample of 36 months already covers up to 530'000 distinct weather years.

Preliminary results suggest that the European energy system requires significantly less backup for security against multi-year energy draughts than today's 2000 TWh of gas and oil reserves. The model chooses fuel storage for multi-year balancing since energy capacity is inexpensive and unconstrained. Hydro reservoirs provide seasonal balancing at cheaper costs, achieving a higher utilization of their scarce capacity . If the import of fossil fuels is permitted, the system has positive emissions in winter months with adverse weather conditions. Direct air capture offsets these emissions during surplus months, particularly in the summer. In conclusion, the developed method and results demonstrate how net-zero systems characterized by weather-dependent supply and demand can manage long-term fluctuations of renewables.

Author: GÖKE, Leonard (ETH Zürich)

Co-authors: Dr MORET, Stefano (ETH Zürich); Prof. BARDOW, André (ETH Zürich)

Presenter: GÖKE, Leonard (ETH Zürich)

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