A pan-European dispatch model for the energy transition in the electricity sector

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I. Motivation

The energy transition:

↳ Increasing penetration of renewable energy sources (RES).

↳ More fluctuating inflexible sources.

↳ Requirement for more flexibility and storage.

How will electricity be produced in the future?

To investigate this question, we develop a pan-European dispatch model and a reliable economic indicator [1].

II. Aggregated electric grid

DC lossless approximation:

$$\sum_i \left(P_i(t) - L_i(t)\right) = 0,\ \forall t \qquad (1)$$

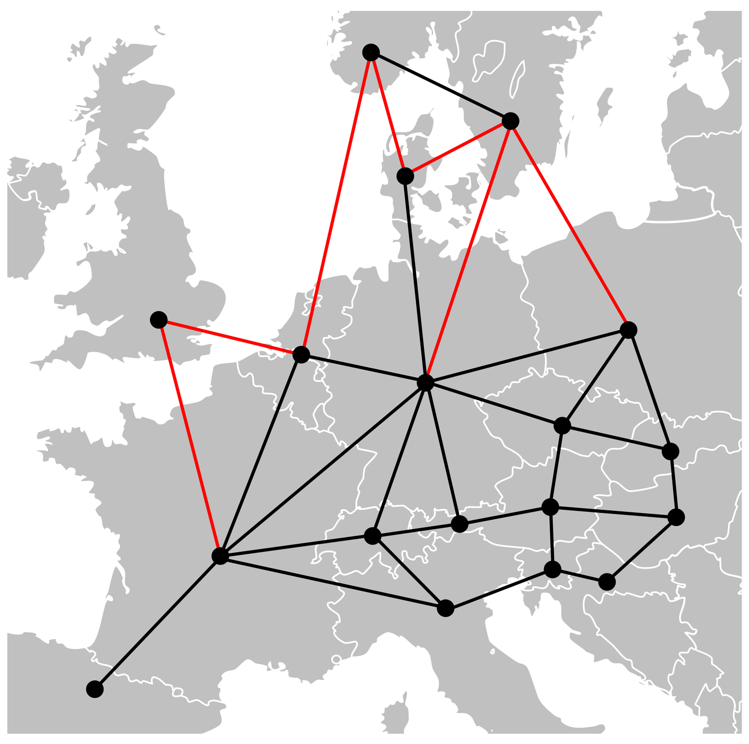

Fig. 1: Aggregated model of the central and northern European grid.

The residual load is the load minus the non-flexible productions,

$$R_i(t) = L_i(t) - P_i^{\rm inflex}(t)\,. \qquad (2)$$

III. Economic dispatch

From Eqs. (1) and (2), the flexible sources must sustain the total residual load

$$\sum_{i,k}\left(P_i^k(t) - R_i(t)\right) = 0,\ \forall t\,. \qquad (3)$$

We introduce a zonal generation cost

$$W_i(t) = \sum_k \left[a^k P_i^k(t) + b^k \frac{P_i^k(t)^2}{P^k_{\max i}}\right]\Delta t\,. \qquad (4)$$

The production profiles are obtained by minimizing the total, annual generation cost

$$W(\{P_i^k(t)\}) = \sum_{i,t} W_i(t)\,, \qquad (5)$$

under the following technical constraints:

Power limits:	$P_i^k(t) \leqslant P^k_{\max i},\ \forall t$
Ramp rates:	$\lvert \partial P_i^k(t)/\partial t\rvert \leqslant \Gamma_i^k,\ \forall t$
Power flows:	$\lvert P_{ij}(t)\rvert \leqslant P_{ij}^{\rm therm}$
Dam storage:	$0 \leqslant S_D(t) \leqslant S_D^{\max},\ \forall t$

References

[1] L. Pagnier and P. Jacquod, *arXiv:1706.01666*, 2017.

[2] ENTSO-E, "ENTSO-E Transparency Platform," https://transparency.entsoe.eu.

[3] ENTSO-E, "TYNDP 2016 Scenario Development Report," http://tyndp.entsoe.eu/.

[4] L. Pagnier and P. Jacquod, *arXiv:1706.00330*, 2017.

IV. Model calibration and validation

We use data from Ref. [2] to set our parameters and to calibrate our model :

- Non-flexible productions of 2015.
- National consumptions of 2015.

We try and reproduce the production profiles of flexible sources.

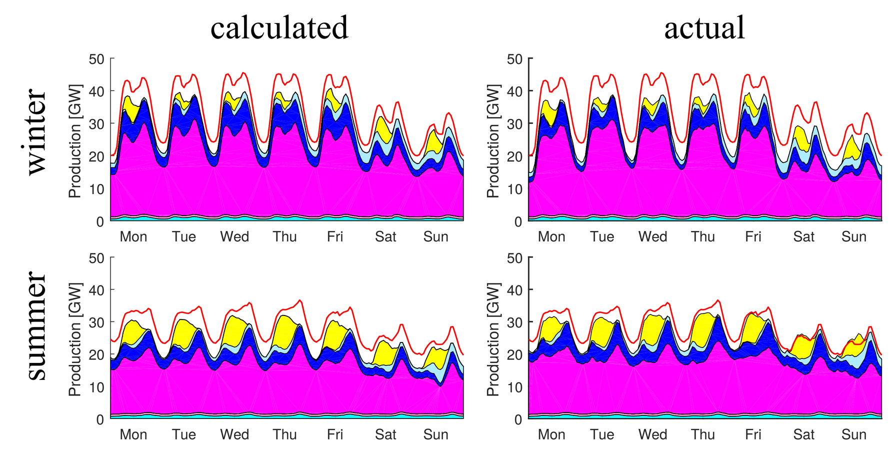

Fig. 2: Italian production in 2015.

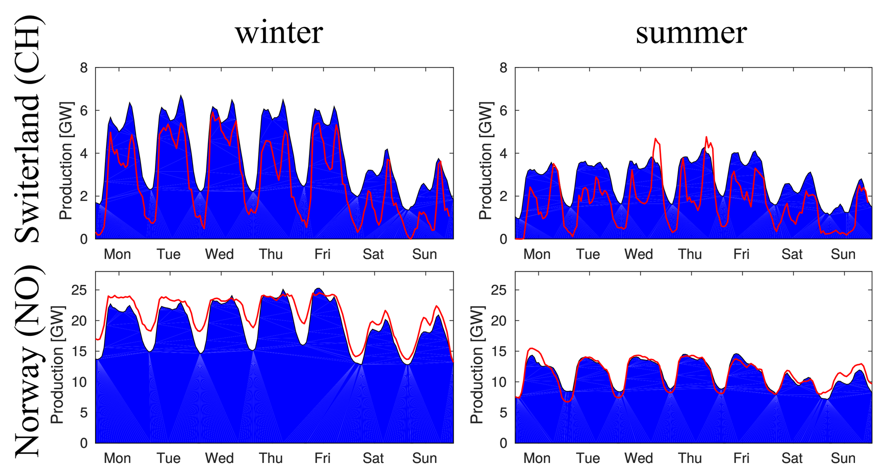

Fig. 3: Calculated (red) and actual (blue) dam production profiles

The model quantitatively reproduces the production profiles of the different flexible sources.

V. Future power dispatch

We assume national consumptions to remain constant and adjust RES profiles:

- National consumptions of 2015.
- RES profiles scaled up to match their expected productions found in Ref. [3].

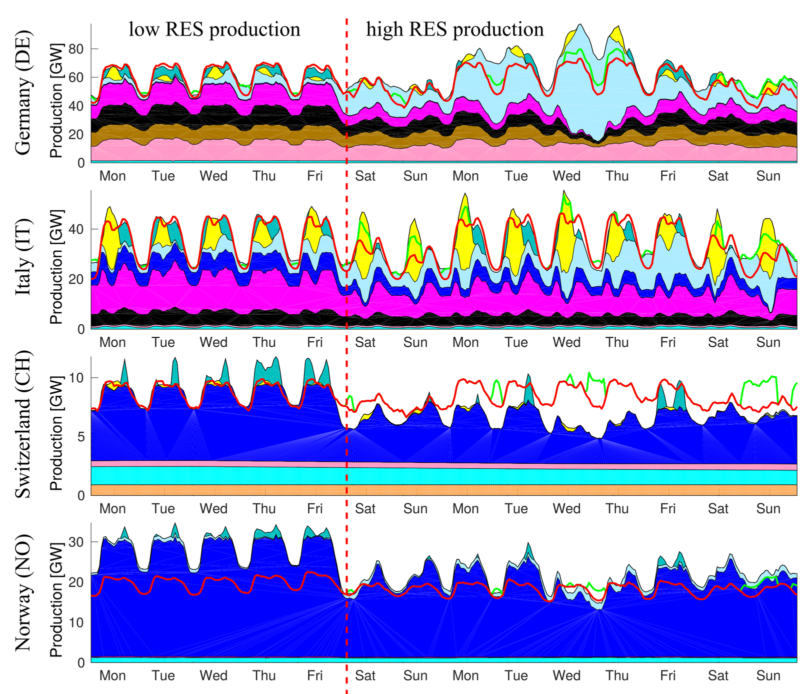

Fig. 4: Future production profiles in winter 2030.

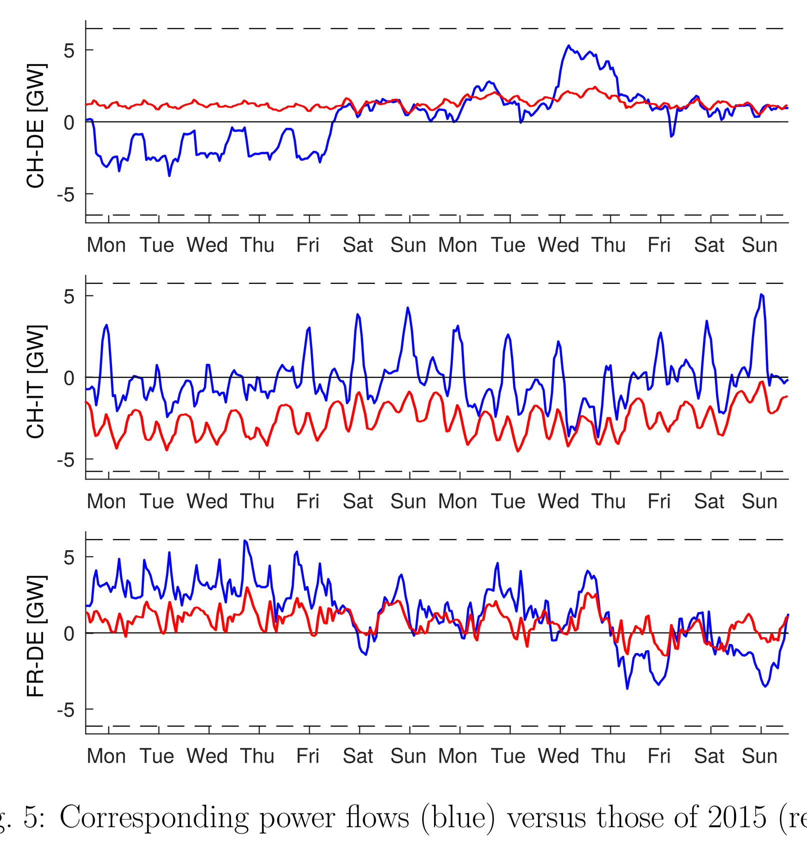

Fig. 5: Corresponding power flows (blue) versus those of 2015 (red).

Figs. 4 and 5 show that

- the production scheme changes.
- more flexibility is asked from dispatchable sources.
- international exchanges are more intensive.

VI. Effective electricity price

Strong correlations exist between residual loads and day-ahead prices.

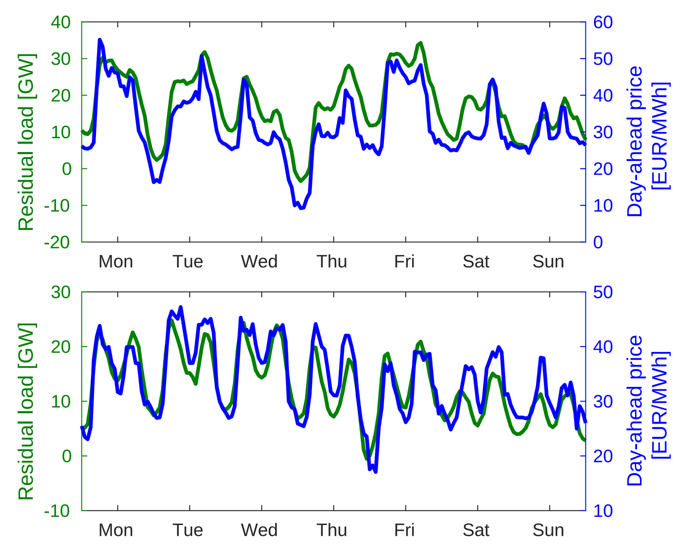

Fig. 6: German residual load and day-ahead electricity price for a winter (top) and summer (bottom) week in 2015.

We define an effective price

$$p_{{\rm eff},i}(t) = \alpha_i R_i(t) + \beta_i\,, \qquad (6)$$

where α_i and β_i are empirically determined national constants.

VII. Revenues of a PS plant

They are obtained from the price defined in Eq. (6) and pump and turbine operations maximizing the following problem

$$G = \sum_k p_{\rm eff}(t_k)[P_{{\rm t}_i}(t_k) - P_{{\rm p}_i}(t_k)]\Delta t \qquad (7)$$

$$\text{s.t. } 0 \leqslant S_{{\rm PS}_i}(t_k) \leqslant S_{{\rm PS}i}^{\max}\ ,\forall k\,. \qquad (8)$$

The storage evolves as

$$S_{{\rm PS}_i}(t+\Delta t) = S_{{\rm PS}_i}(t) + [\eta P_{{\rm p}_i}(t) - \eta^{-1}P_{{\rm t}_i}(t)]\Delta t\,. \qquad (9)$$

Fig. 7 shows the optimized production profile of a pumped-storage plant.

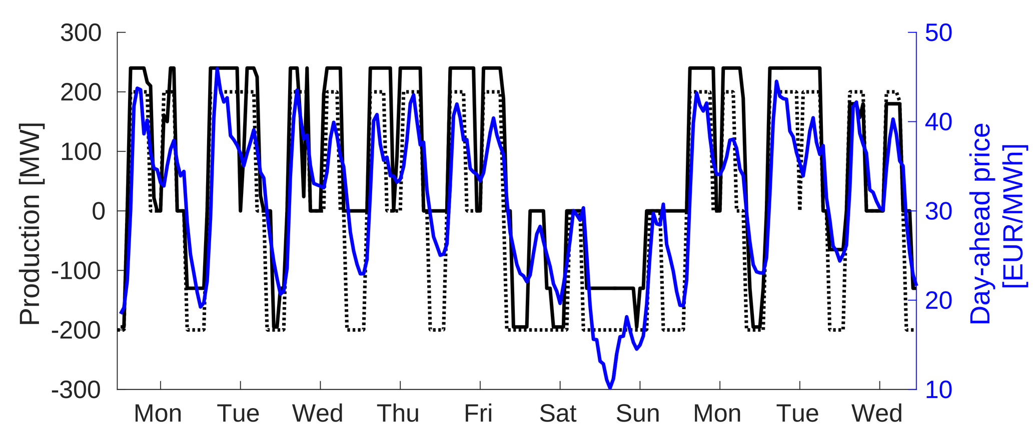

Fig. 7: Optimized production of a PS plants.

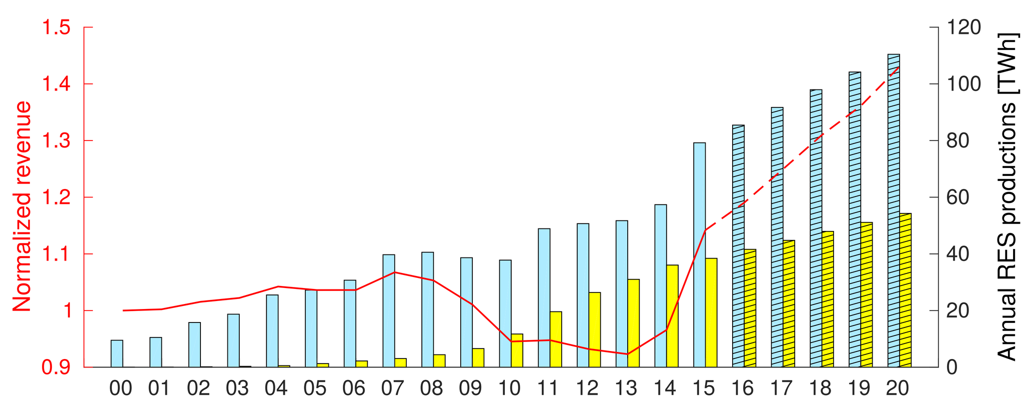

Fig. 8: Normalized revenue for a PS plant (red line) superimposed on annual production for PV (yellow) and wind turbines (light blue) in Germany.

Revenues of a PS plant are nonmonotonous as the RES penetration increases.

VIII. Conclusion

We constructed a pan-European model for the future electricity market and an economic predictor.

Findings:

- Large penetration can be achieved with more cooperation and intensive usage of available flexibility.
- The sooner the energy transition will reach a mature stage, the quicker revenues of pumped-storage plants (and of hydroelectricity in general) will reincrease.

More information on the residual load as an effective price in Ref. [4].