A predictive pan-European economic and production dispatch model for the energy transition in the electricity sector

Laurent Pagnier
Institute of Theoretical Physics
École Polytechnique Fédérale de Lausanne
Lausanne, Switzerland
laurent.pagnier@epfl.ch

Philippe Jacquod
School of Engineering
University of Applied Sciences of Western Switzerland
Sion, Switzerland
philippe.jacquod@hevs.ch

Abstract—The energy transition is well underway in most European countries. It has a growing impact on electric power systems as it dramatically modifies the way electricity is produced. To ensure a safe and smooth transition towards a pan-European electricity production dominated by renewable sources, it is of paramount importance to anticipate how production dispatches will evolve, to understand how increased fluctuations in power generations can be absorbed at the pan-European level and to evaluate where the resulting changes in power flows will require significant grid upgrades. To address these issues, we construct an aggregated model of the pan-European transmission network which we couple to an optimized, few-parameter dispatch algorithm to obtain time- and geographically-resolved production profiles. We demonstrate the validity of our dispatch algorithm by reproducing historical production time series for all power productions in fifteen different European countries. Having calibrated our model in this way, we investigate future production profiles at later stages of the energy transition – determined by planned future production capacities – and the resulting interregional power flows. We find that large power fluctuations from increasing penetrations of renewable sources can be absorbed at the pan-European level via significantly increased electricity exchanges between different countries. We identify where these increased exchanges will require additional power transfer capacities. We finally introduce a physically-based economic indicator which allows to predict future financial conditions in the electricity market. We anticipate new economic opportunities for dam hydroelectricity and pumped-storage plants.

Index Terms—Electricity market, power generation dispatch, power Transmission.

I. INTRODUCTION

Most European countries are now engaged in the energy transition whose ultimate goal is to meet energy demand from human activities solely with renewable energy sources (RES). In its current intermediate stages, the transition steadily increases the penetration of nondispatchable electricity productions, which results in large uncontrolled fluctuations in power generation. The development of RES in Europe follows from strong public investments and incentives which temporarily bias the electricity market. RES have negligible marginal cost and consequently their increasing penetration artificially lowers electricity prices below production costs for many other power generations. Simultaneously, new RES such as solar photovoltaics and wind turbines have undispatchable, strongly fluctuating productions which need to be counterbalanced by controllable, dispatchable productions and electrical energy storage solutions. In the context of the energy transition it is therefore of key importance to understand how RES penetrations can be increased without jeopardizing the dispatchable productions required by the next level of RES penetration.

One of our main interests here is the hydroelectric sector, with its fast dispatchable and fully controllable dam productions as well as pumped-storage (PS), the only sizeable, mature storage solution to date. Hydroelectricity seems like an ideal partner to RES in the context of the energy transition and one may anticipate that further investments in new PS or higher power dam facilities would significantly help to absorb increased production fluctuations from larger RES penetrations. However, somewhat ironically, the current low electricity prices penalize investments in new hydroelectric facilities – with today’s economic conditions in the European electric sector, RES jeopardize the future of hydroelectricity, arguably one of its main and most reliable future partner. To evaluate scenarios for the energy transition it is therefore of paramount importance to evaluate whether this trend will continue, and if yes, for how long, and determine if and when the precious flexibility of hydroelectric production will be again rewarded. To achieve that, one needs a reliable dispatch model for all types of electric productions as well as a reliable economic indicator. The current electricity market requires tools for financial analysis with increased precision to identify the need for further production investments and the returns they will generate. Of particular interest is to try and implement transparent dispatch models at the level of the pan-European grid that rely as weakly as possible on highly volatile political, economical or financial predictions.

In this manuscript, we develop an integrated physically-economic power dispatch model relying on physical constraints for electric power productions, on published future production capacity developments and on basic, demand-supply economical laws only. We demonstrate the validity of
our model by reproducing rather accurately historical 2015 electricity production profiles for all power production types in nineteen European countries. We argue that our model will become more and more accurate as the energy transition progresses and investigate European dispatches as well as intercountry exchanges for 2030. This allows us to identify the needs for increased grid capacity, for further storage capacity as well as future rules of engagement for hydroelectric dam power plants. Additionally, we clarify the financial conditions prevailing in the electricity market in the forthcoming stages of the energy transition.

The main limitation of our approach is related to uncertainties in future installed production capacities in European countries, which will depend on more general economic and financial conditions in Europe and in the world as well as on future political and societal decisions. However, regardless of these mostly unpredictable conditions, we argue that our dispatch and revenue evaluation model retains its validity, provided production capacities are adapted to their true evolution. In other words, our model qualitatively predicts production dispatches and revenues for given production capacities. Accordingly, feasibility studies should consider various scenarios for future production capacities to investigate which one presents the best operational and financial perspectives.

The manuscript is organized as follows. In Section II we discuss our aggregated pan-European power grid model, the optimal power flow and the parameters on which our dispatch model is based. In Section III we calibrate these parameters by reproducing historical data for the year 2015. In Section IV, we apply our model to one ENTSO-E scenario for future European electric power production capacities for the year 2030. Our results show how electric power is transferred across the continent as different meteorological conditions prevail, and from this, we infer the magnitude of intercountry power flows. In Section V we introduce the residual load as an economic indicator which allows us to evaluate normalized future revenues. As an example we calculate future revenues for pumped-storage hydroelectric power plants in Germany. Conclusions and discussions of our results and our model are presented in Section VI.

II. AN AGGREGATED MODEL FOR FUTURE PAN-EUROPEAN ELECTRICITY DISPATCH

We develop an equivalent model to determine future power dispatches in the pan-European power grid at different stages of the energy transition. Equivalent aggregated models have a relatively long history [1]–[3]. They are standardly used for systemic investigations such as ours, where precise details of power flows are not crucial (as opposed to, say, grid stability investigations) and exact, geographically resolved production and consumption data are hard to obtain.

A. An aggregated pan-European electric grid

Fig. 1 shows our aggregated European grid, with each node representing an independent dispatch zone (Portuguese consumption and production are included in the Spain node).

Aggregated lines have admittances obtained via a standard reduction method [4] and thermal limits given by the sum of the physical lines they represent. The power flows are computed in the DC lossless approximation [5].

B. Productions and Consumptions

Consumptions and productions are aggregated within each dispatch region and attributed to the corresponding node. Power productions are subdivided into two sets. They are,

- Non-flexible productions, mostly consisting of run-of-the-river (RoR), solar photovoltaics (PV) and wind turbine productions. The remaining non-flexible productions are grouped into "miscellaneous productions". Note that RoR is in principle flexible, at least to some extent, however we neglect curtailment and consider that, as for PV and wind turbines, RoR production is determined by weather/seasonal conditions only.
- Flexible productions: We classify them into 6 types, which are (i) dam hydroelectricity, (ii) pumped-storage hydroelectricity (which can be positive as well as negative, but always counted as a production), (iii) gas and oil, (iv) nuclear, (v) hard coal and (vi) lignite productions.

For each zone and at each time, we define the residual loads $R_{i}(t)$ as the difference between the consumption and the non-flexible productions,

$$R_{i}(t) = L_{i}(t) - P_{i}^{\text{inflex}}(t),$$

where $L_{i}(t)$ and $P_{i}^{\text{inflex}}(t)$ respectively give the load and the sum of the non-flexible productions at time $t$ in the $i^{th}$ zone. In our approach, non-flexible sources produce according to weather and seasonal conditions, and only flexible productions are dispatchable. Our task is therefore to dispatch all flexible
productions so that their production is equal to the total residual load at all times - this is equivalent to satisfy the balance condition that consumption is equal to production at all times.

The association of European transmission grid operators (ENTSO-E) provides data on historical production and load profiles and installed capacities in the different countries \cite{6} and forecasts for annual RES productions \cite{7,8} that we use to set up our model.

C. Economic dispatch

A large number of different optimized power flows exist \cite{9-13}. Our dispatch algorithm follows a merit order. The latter is based, first, on marginal costs, \( a^k \), specific to each production type, \( k \). Second, we introduce effective parameters in the form of repulsion costs, \( b^k \), which progressively increase the total production cost as the production increases and reaches its maximal possible value. Such repulsion costs do not directly correspond to any real economic cost, however we found that they are necessary to smoothen production curves and reproduce historical time series faithfully. With these two parameters for each of the six different flexible productions, our model has a total of 12 parameters that need to be calibrated.

The production cost in the \( i^{th} \) zone at each time step \( \Delta t = 1 \)h is given by a sum over the marginal and repulsion costs for all production types as

\[
W_i(t) = \sum_k \left[ a^k P^k_i(t) + b^k \frac{P^k_i(t)^2}{P^{\max k}_i} \right] \Delta t,
\]

(2)

where \( P^k_i(t) \) is the power generated by a given production type labelled \( k \), in a geographical zone labelled \( i \), at time \( t \), and \( P^{\max k}_i \) is the corresponding installed capacity. Our algorithm is based on an optimal power flow which determines the production profiles \( \{ P^k_i(t) \} \) minimizing the total, annual generation cost

\[
W(\{ P^k_i(t) \}) = \sum_{i,t} W_i(t),
\]

(3)

under the following technical constraints:

a) Power limits: \( P^k_i(t) \leq P^{\max k}_i \), \( \forall t \); the power generated never exceeds its maximal installed capacity.

b) Ramp rates: \( |\partial P^k_i(t)/\partial t| \leq \Gamma^k_i \), \( \forall t \); each production type has a maximal ramp rate \( \Gamma^k_i \) at which the production increases or decreases. These ramp rates are similar, but not exactly equal, to the real, technical rates. We adapted them slightly when calibrating our model, to reproduce historical production time series better.

c) Internodal power flows: \( |P_{ij}(t)| \leq P^\text{therm}_{ij} \); they should never exceed the thermal limit \( P^\text{therm}_{ij} \) of the aggregated line between node \( i \) and \( j \) that carries them; when they do, a different dispatch must be implemented to correct this.

d) Dam storage: Dam hydroelectric plants are constrained by the finiteness of their reservoir and the annual water intake into the latter.

III. MODEL CALIBRATION

To calibrate the parameters in our model, we fixed nonflexible productions to those of 2015 and optimized the 12 parameters in our model to reproduce true 2015 production data as faithfully as possible. In Fig. 2 we show the result for a winter and a summer week in Germany and Italy, after the 12 parameters have been optimized. The agreement between dispatched and actual productions is excellent. We found comparable agreement between calculated and real 2015 productions for all other countries in our aggregated
model. Another level of complexity is brought about by dam hydroelectricity with its great flexibility. To illustrate that our dispatch model works even in that case, we show in Fig. 3 the productions of Swiss and Norwegian dam hydroelectric plants during one week in summer and winter. Despite the inherent difficulty to dispatch dam hydro production, we see that our model captures most features of the 2015 production rather faithfully. Few discrepancies exist, in particular our calculation oversuses flexibility in Norway in winter, which we attribute to mid- and long-term supply contracts whose effect cannot be captured by our model. Even with these few discrepancies, we are unaware of another model that captures the national productions up to this level of detail at a European scale, including hydroelectric productions. From Fig. 4 and 5 we conclude that our model is calibrated and fully valid. Its 12 free parameters having been fixed, we next use the model to investigate future scenarios of the energy transition.

IV. FUTURE POWER DISPATCH

Having calibrated our model, we next investigate how the flexible productions are dispatched, both geographically and in time, to handle future large penetration of RES in later stages of the energy transition. Our results are based on three assumptions. First, for production capacities in each country, we use the ENTSO-E scenario 2030 Vision 4 of European Green Revolution [8]. Second, non-flexible productions are obtained by rescaling their 2015 production profiles in direct proportion to their capacity evolution. Third, we assume that consumption profiles will not be too different in 2030 from what they are now and use 2015 consumption profiles for each country in the aggregated model of Fig. 1. Obviously, our model can be used to check any other production and consumption scenario one may wish to implement.

Fig. 4 shows the productions of Germany, Italy, Switzerland and Norway for two consecutive weeks in the winter of 2030. One sees first that when RES have low production (first five days), dam hydro productions are high to help supplying the demand for electricity. When RES productions are high, dam hydro production is significantly lowered. In particular, one sees that, with large RES productions, Switzerland continuously imports electricity during several consecutive days, which is never the case nowadays. Pump-storage hydro is additionally intensively used, as it produces a lot when RES produce little and consumes (pumps) when RES productions are high. The yearly dam hydro production corresponds to the yearly water intake and as it is not expected to change significantly in the next two decades, the annual productions of Norway and Switzerland are comparable to the 2015 productions. Note that the total Swiss production diminishes a bit significantly in the next two decades, the annual productions of Norway and Switzerland are comparable to the 2015 productions. Note that the total Swiss production diminishes a bit compared to 2015, which is due to the incomplete substitution of dismantled nuclear power by RES in the chosen ENTSO-E scenario for Switzerland.

Fig. 5 shows the power flow of three important interconnects for the same two weeks. For comparison we added the power flows obtained for 2015 for the same period. We observe that more flexibility is asked of dispatchable productions. In particular, the flows in 2015 tend to have a dominant direction. For instance, the CH-IT connection is used for Italian import overuses flexibility in Norway in winter, which we attribute to mid- and long-term supply contracts whose effect cannot be captured by our model. Even with these few discrepancies, we are unaware of another model that captures the national productions up to this level of detail at a European scale, including hydroelectric productions. From Fig. 4 and 5 we conclude that our model is calibrated and fully valid. Its 12 free parameters having been fixed, we next use the model to investigate future scenarios of the energy transition.

IV. FUTURE POWER DISPATCH

Having calibrated our model, we next investigate how the flexible productions are dispatched, both geographically and in time, to handle future large penetration of RES in later stages of the energy transition. Our results are based on three assumptions. First, for production capacities in each country, we use the ENTSO-E scenario 2030 Vision 4 of European Green Revolution [8]. Second, non-flexible productions are obtained by rescaling their 2015 production profiles in direct proportion to their capacity evolution. Third, we assume that consumption profiles will not be too different in 2030 from what they are now and use 2015 consumption profiles for each country in the aggregated model of Fig. 1. Obviously, our model can be used to check any other production and consumption scenario one may wish to implement.

Fig. 4 shows the productions of Germany, Italy, Switzerland and Norway for two consecutive weeks in the winter of 2030. One sees first that when RES have low production (first five days), dam hydro productions are high to help supplying the demand for electricity. When RES productions are high, dam hydro production is significantly lowered. In particular, one sees that, with large RES productions, Switzerland continuously imports electricity during several consecutive days, which is never the case nowadays. Pump-storage hydro is additionally intensively used, as it produces a lot when RES produce little and consumes (pumps) when RES productions are high. The yearly dam hydro production corresponds to the yearly water intake and as it is not expected to change significantly in the next two decades, the annual productions of Norway and Switzerland are comparable to the 2015 productions. Note that the total Swiss production diminishes a bit compared to 2015, which is due to the incomplete substitution of dismantled nuclear power by RES in the chosen ENTSO-E scenario for Switzerland.

Fig. 5 shows the power flow of three important interconnects for the same two weeks. For comparison we added the power flows obtained for 2015 for the same period. We observe that more flexibility is asked of dispatchable productions. In particular, the flows in 2015 tend to have a dominant direction. For instance, the CH-IT connection is used for Italian import overuses flexibility in Norway in winter, which we attribute to mid- and long-term supply contracts whose effect cannot be captured by our model. Even with these few discrepancies, we are unaware of another model that captures the national productions up to this level of detail at a European scale, including hydroelectric productions. From Fig. 4 and 5 we conclude that our model is calibrated and fully valid. Its 12 free parameters having been fixed, we next use the model to investigate future scenarios of the energy transition.

IV. FUTURE POWER DISPATCH

Having calibrated our model, we next investigate how the flexible productions are dispatched, both geographically and in time, to handle future large penetration of RES in later stages of the energy transition. Our results are based on three assumptions. First, for production capacities in each country, we use the ENTSO-E scenario 2030 Vision 4 of European Green Revolution [8]. Second, non-flexible productions are obtained by rescaling their 2015 production profiles in direct proportion to their capacity evolution. Third, we assume that consumption profiles will not be too different in 2030 from what they are now and use 2015 consumption profiles for each country in the aggregated model of Fig. 1. Obviously, our model can be used to check any other production and consumption scenario one may wish to implement.

Fig. 4 shows the productions of Germany, Italy, Switzerland and Norway for two consecutive weeks in the winter of 2030. One sees first that when RES have low production (first five days), dam hydro productions are high to help supplying the demand for electricity. When RES productions are high, dam hydro production is significantly lowered. In particular, one sees that, with large RES productions, Switzerland continuously imports electricity during several consecutive days, which is never the case nowadays. Pump-storage hydro is additionally intensively used, as it produces a lot when RES produce little and consumes (pumps) when RES productions are high. The yearly dam hydro production corresponds to the yearly water intake and as it is not expected to change significantly in the next two decades, the annual productions of Norway and Switzerland are comparable to the 2015 productions. Note that the total Swiss production diminishes a bit compared to 2015, which is due to the incomplete substitution of dismantled nuclear power by RES in the chosen ENTSO-E scenario for Switzerland.

Fig. 5 shows the power flow of three important interconnects for the same two weeks. For comparison we added the power flows obtained for 2015 for the same period. We observe that more flexibility is asked of dispatchable productions. In particular, the flows in 2015 tend to have a dominant direction. For instance, the CH-IT connection is used for Italian import overuses flexibility in Norway in winter, which we attribute to mid- and long-term supply contracts whose effect cannot be captured by our model. Even with these few discrepancies, we are unaware of another model that captures the national productions up to this level of detail at a European scale, including hydroelectric productions. From Fig. 4 and 5 we conclude that our model is calibrated and fully valid. Its 12 free parameters having been fixed, we next use the model to investigate future scenarios of the energy transition.
exchanges between European countries, often reversing the
direction of the power flows and leading the latter regularly
close to their thermal limits and sometimes in an unexpected
direction.

V. EFFECTIVE ELECTRICITY PRICE

To anticipate changes and necessary upgrades to electric
power systems in the light of the energy transition, a reliable
economic indicator is needed which gives a qualitatively reli-
able estimate for the price of electricity. Here we deliberately
choose to use an indicator solely based on technico-physical
conditions and not on highly speculative economic forecasts.
As a matter of fact, such an economic indicator exists, which
reflects quite clearly the law of supply and demand: it is
important to supply what is demanded. As a matter of fact, such an
economic indicator exists, which reflects quite clearly the law of supply and
demand: it is important to supply what is demanded.

Fig. 6. German residual load (green line) and the German day-head electricity
price (blue) for a winter (top) and summer (bottom) week in 2015. There exists
a clear, almost perfect correlation between the two quantities.

with two parameters $\alpha_i$ and $\beta_i$ to be empirically deter-
ted from historical data. We obtained estimates $\alpha_i \approx 1$ [EUR/(MWh $\cdot$ GW)] and $\beta_i \approx 20$ [EUR/MWh] from recent
historical data for Germany.

Having introduced this effective electricity price, it is now
possible to investigate future economic conditions and oppor-
tunities with our model. To illustrate this, we evaluate
future economic conditions for pumped-storage (PS) power
plants. The revenue generated by a PS plant depends on its
pump/turbine powers $P_p(t)$ and $P_t(t)$, and the filling $S_{PS}(t)$
of its reservoirs as

$$
G = \sum_k p_{eff}(t_k)[P_t(t_k) - P_p(t_k)] \Delta t
$$

s.t. $0 \leq S_{PS}(t_k) \leq S_{PS}^{max}$, $\forall k$.

At each time step $\Delta t = 1$ h, the reservoir filling evolves as

$$
S_{PS}(t + \Delta t) = S_{PS}(t) + [\eta P_p(t) - \eta^{-1} P_t(t)] \Delta t
$$

with a typical pump/turbine efficiency of $\eta = 0.9$. Including
hydro pumped-storage defined by Eqs. (5–7), our pan-
European aggregated model is similar to the power-node
model of Ref. [13].

To obtain the PS production/consumption profile, we
include its effective revenue, $G$, in Eq. (5), in the total gain $W$
to optimize [see Eq. (3)], and the constraints of Eqs. (6) and
(7) into our aggregated model. Fig. 7 shows time profiles for
PS production/consumption, electricity prices and PS reservoir
level for a fictitious 1 GW, 32 GWh PS plant. The production
profile is, as expected, clearly correlated with the electricity
price, and the constraints on the reservoir level are met.

The PS revenue is further calculated using Eq. (5) and
we plot it in Fig. 8 for the special case of Germany. Data
are superimposed on histograms depicting the annual RES
electricity production for PV (yellow) and wind turbines (light
blue). We normalized the revenue with the revenue obtained
from our dispatch model for the year 2000. We correctly obtain
Fig. 8. Normalized revenue for PS (red line) superimposed on annual production for PV (yellow) and wind turbines (light blue) in Germany. A pump-storage efficiency of $\eta = 0.9$ each way is assumed.

a significant revenue reduction from 2008 on, with a minimum around 2013, after which the revenue increases again to get back to its pre-2008 value at around 2015-2016. The latter behavior is likely a bit premature, however, overall, our data qualitatively suggest that, (i) after a period of difficulties, PS will get back to its pre-2008 profit level rather soon, at least in Germany, and (ii) how soon PS gets back to larger profit margins depends mostly on how fast RES are substituted for fossil productions.

VI. CONCLUSIONS

We have constructed a pan-European model for the future electricity market. Using a mathematically well-defined merit order, we calibrated it so that it reproduces 2015 production profiles. We investigated how productions will change up to 2030 and found that enhanced intercountry power exchanges will help absorbing large fluctuations of productions from PV and wind turbines. We introduced an effective electricity price and illustrated its predictive power by investigating revenues generated by pump-storage facilities in Germany. Our results suggest that hydro pump-storage power plants will again generate comfortable profits in the future. How soon that will be depends mostly on the pace at which the energy transition proceeds.

ACKNOWLEDGMENT

This work has been supported by the Swiss National Science Foundation.

REFERENCES

[1] J. B. Ward, “Equivalent circuits for power-flow studies,” Electrical Engineering, vol. 68, no. 9, pp. 794–794, 1949.
[2] W. F. Tinney and J. M. Bright, “Adaptive reductions for power flow equivalents,” IEEE Transactions on Power Systems, vol. 2, no. 2, pp. 351–359, 1987.
[3] A. Papaemmanouil and G. Andersson, “On the reduction of large power system models for power market simulations,” in 17th Power Systems Computation Conference (PSCC), 2011, pp. 1308–1313.
[4] D. Shi and D. J. Tylavsky, “A novel bus-aggregation-based structure-preserving power system equivalent,” IEEE Transactions on Power Systems, vol. 30, no. 4, pp. 1977–1986, 2015.
[5] A. Gómez-Expósito, A. J. Conejo, and C. Cañizares, Electric energy systems: analysis and operation. CRC Press, 2008.
[6] ENTSO-E, “Ensto-e transparency platform,” https://transparency.entsoe.eu.
[7] ENTSO-E, “Mid term adequacy forecast,” https://www.entsoe.eu/outlooks/mail/Pages/default.aspx.
[8] ——, “Tyndp 2016 scenario development report,” http://tyndp.entsoe.eu.
[9] G. Czisch, “Szenarien zur zukünftigen Stromversorgung: kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien,” Ph.D. dissertation, Universität Kassel, 2005.
[10] K. Schaber, F. Steinke, and T. Hamacher, “Transmission grid extensions for the integration of variable renewable energies in Europe: Who benefits where?” Energy Policy, vol. 43, pp. 123–135, 2012.
[11] F. Comaty, A. Ulbig, and G. Andersson, “Ist das geplante Stromsystem der Schweiz für die Umsetzung der Energiestrategie 2050 aus technischer Sicht geeignet?” 2014.
[12] R. A. Rodriguez, S. Becker, and M. Greiner, “Cost-optimal design of a simplified, highly renewable pan-European electricity system,” Energy, vol. 83, pp. 658–668, 2015.
[13] J. Schwippe, A. Seack, and C. Rehtanz, “Pan-European market and network simulation model,” in PowerTech (POWERTECH), 2013 IEEE Grenoble. IEEE, 2013, pp. 1–6.
[14] M. Huber and S. von Roos, “Modeling spot market pricing with the residual load,” 2010.
[15] K. Heussen, S. Koch, A. Ulbig, and G. Andersson, “Energy storage in power system operation: The power nodes modeling framework,” Proc. IEEE PES Conf. Innovative Smart Grid Technol, 2010.