The Grengiols–Saflischtal Photovoltaic Solar Farm: an Independent Analysis

Julian Fritzsch[1,2], Philippe Jacquod[1,2], and Laurent Pagnier[3]

[1] *Department of Quantum Matter Physics - University of Geneva - 1211 Geneva*

[2] *School of Engineering - University of Applied Sciences of Western Switzerland - 1951 Sion and*

[3] *Program in Applied Mathematics - University of Arizona - Tucson Arizona 85721*

(Dated: October 26, 2022)

I. SUMMARY

With the current energy crisis affecting Europe and Switzerland in particular, efficient new generations of electric power are urgently needed. In this context, a number of proposals has been put forward to increase our country's renewable electricity production [1]. One such project is the Grengiols–Saflischtal solar power plant [2]. The project is still in an early developmental stage and quantitatively reliable numbers for power production capacity and annual energy generation do not truly exist. Given a potential area of $5\,\mathrm{km}^2$, an upper bound for the plant's peak power is in the $1\,\mathrm{GW_p}$ range, which, given the plant's location and panel orientation may generate as much as 1.5 TWh to 2 TWh annually for bifacial photovoltaic panels [3]. These numbers sound rather optimistic, but regardless of their accuracy, electric power generation in the range of hundreds of megawatts can only be injected into the grid at extra-high voltages of 220 kV or 380 kV, therefore, a question that naturally arises is whether Switzerland's transmission grid can safely absorb this additional power injection.

In this report, we evaluate the maximal peak electric power that a large solar photovoltaic farm in the Grengiols–Saflischtal area could safely inject into Switzerland's extra-high voltage grid, without jeopardizing its stability. We consider two different grids: (i) the current extra-high voltage grid operated by Swissgrid as of October 2022, and (ii) Swissgrid's strategic grid 2025, which will be finalized no earlier than 2028. Our main findings are that:

- When completed, Swissgrid's strategic grid 2025 will be able to absorb more than $1\,\mathrm{GW_p}$ of photovoltaic peak power injection at Mörel's substation, but not at Fiesch. This is so, because Mörel is a "hub" between 380 kV and 220 kV so that an injection at 380 kV can be transmitted on two lines, east- and westward, each with a capacity of $\sim$1.7 GW, and additionally to the level through a 700 MW transformer. The Fiesch substation on the other hand only connects to the 220 kV line and accordingly has a significantly smaller power capacity.

- Without either the westward 380 kV line from Mörel to Chippis or the eastward 380 kV from Mörel to Lavorgo (via Ulrichen and Airolo), it is not possible to absorb $1\,\mathrm{GW_p}$ at Mörel's substation. Therefore, Switzerland's current extra-high voltage grid may safely absorb $300\,\mathrm{MW_p}$, but not much more than that. Injection at the Fiesch substation would be further restricted.

- An extra-high voltage power line needs to be constructed to connect the plant to a substation on Swissgrid's transmission grid.

According to Swissgrid, the Chippis-Mörel 380 kV line will be completed no earlier than 2028,[1] while construction of the Airolo-Lavorgo 380 kV line will not start before 2024. We therefore conclude that the project, with its announced potential of $2\,\mathrm{GW_p}$, cannot be completed/connected to the grid before at least 2028. A scaled-down project with a power production around $300\,\mathrm{MW_p}$ could be connected to the currently operational extra-high voltage grid.

Complete feasibility studies should investigate further necessary infrastructures such as (i) the power line necessary to connect the photovoltaic farm to the transmission grid, (ii) large-scale converters and other essential power electronics infrastructures necessary to inject current into the power grid and (iii) possible electric storage solutions to smoothen power injections into the transmission grid.

[1] See www.swissgrid.ch/en/home/projects/project-overview.html

II. CONTEXT

A. The project and its general features

With the current energy crisis impacting Europe, efficient new generations of electric power are urgently needed. In this context, a number of proposals have been put forward for increasing Switzerland's electricity production [1]. One such project is the Grengiols–Saflischtal photovoltaic power plant. In its early proposal form, it would cover an area as large as $5\,\mathrm{km}^2$ at an altitude of 2000 m and above. The general location is sketched in Fig. 1. At the time of writing this report, the project is not sufficiently advanced that location and/or geographical extension can be precisely determined. Therefore Fig. 1 is only indicative of the project's general geographical context.

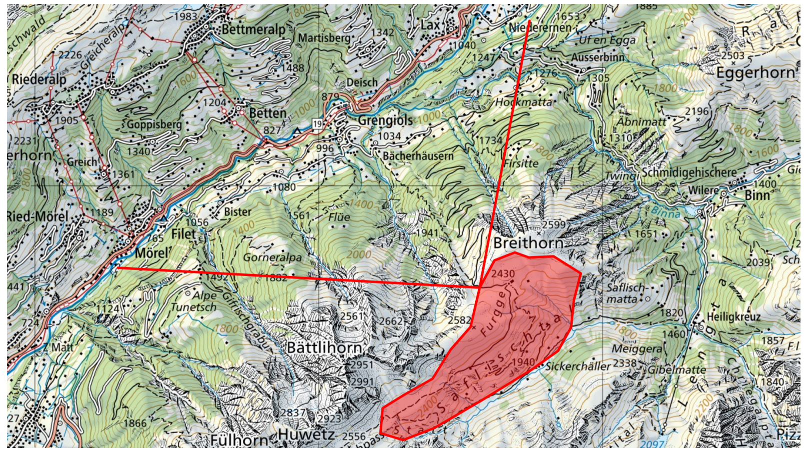

FIG. 1. Approximate situation of the projected Grengiols–Saflischtal photovoltaic solar farm. Red lines are guides to the eye and illustrate potential very high voltage lines to be constructed, to connect the farm to existing or planned substations in Switzerland's extra-high voltage grid.

Numbers expressed so far put its annual production of electrical energy at 2 TWh, for a peak power in the range $1.5\,\mathrm{GW_p}$ to $2\,\mathrm{GW_p}$ [2]. Looking at the average power density per area of existing large photovoltaic farms [4], we note that a peak capacity of around $300\,\mathrm{MW_p}$ sounds more realistic, given the average power density of ca. $60\,\mathrm{MW_p/km^2}$ extracted from Ref. [4]. We nevertheless include solar injections in the range of one gigawatt and above in our investigations.

A presupposed advantage of the proposed high-altitude project location is often put forward: with bifacial panels and the right orientation, it could presumably produce as much energy in winter as in summer. Measurements on single panels indeed demonstrate such effect [3], and it is implicitly assumed that these results would scale up with the size of the plant. Such projects therefore attract a maximal attention almost immediately, as they could potentially solve Switzerland's main electricity problem – its lack of winter production.

While the so-far suggested nameplate capacity and annual production numbers of this project, as well as their seasonality seem to lie on the optimistic side to us, we do not debate them here, nor do we discuss all the necessary infrastructures to connect such a large power injection to the transmission grid. Instead, we restrict ourselves to investigating what would be required to inject such peak power into Switzerland's extra high voltage power grid. It must be clear that such a high power needs to be injected at extra high voltages, i.e., 220 kV or 380 kV. This is so because first, $1\,\mathrm{GW_p}$ exceeds the maximal total power load of the Valais Canton, therefore it needs to be transported beyond its border, and that can be done only via the extra-high voltage grid. Second, electric power transmission over extra high voltages reduces ohmic losses and accordingly improves energy efficiency: at lower voltages, carrying the same amount of power requires larger currents, generating larger ohmic losses.

B. Switzerland's current and future transmission grids

The main question we ask is whether the current transmission grid of Switzerland, or Swissgrid's strategic grid 2025, would be able to absorb the injection of $1\,\mathrm{GW_p}$ to $2\,\mathrm{GW_p}$ somewhere between Mörel and Fiesch. Both Switzerland's current extra-high voltage grid and the strategic grid 2025 are shown in Fig. 2. Of particular importance to answer this question is the local part of the grid close to the proposed plant. Fig. 3 offers a closer look on the extra-high voltage power grid in the vicinity of the proposed solar farm.

The left panel of Fig. 3 shows that there are only 220 kV lines, each with a thermal limit of ca. 350 MW to 450 MW, in the current grid. Injection of power into that grid may occur only at substations, which are indicated by empty circles. There are two such substations near the Grengiols–Saflischtal project – Mörel and Fiesch. Five 220 kV lines are connected at the Mörel substation, which therefore seems like an injection station of choice for any additional power production. Note that the line towards Gabi and Serra continues to Italy, while the line south of Stalden ends

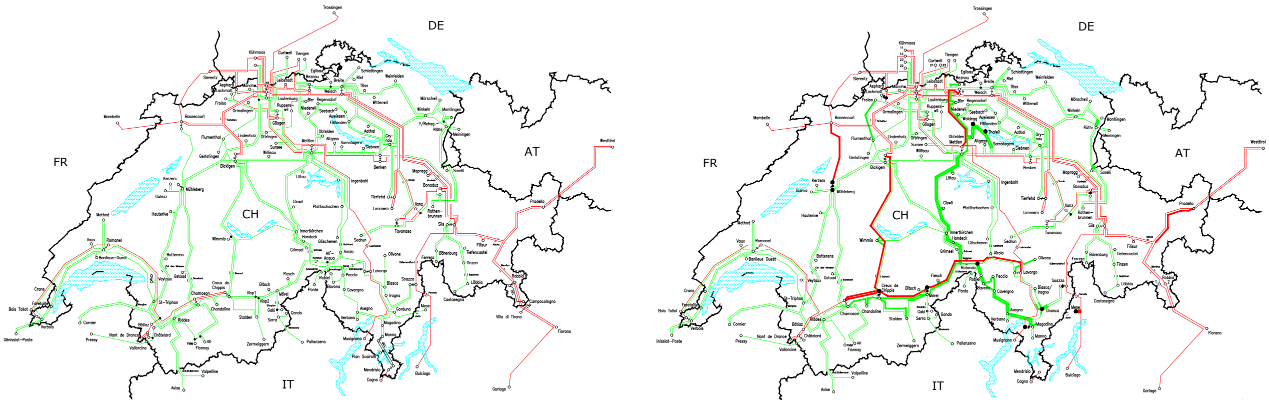

FIG. 2. Left: current Swiss extra-high voltage power grid operated by Swissgrid as of October 2022. Right: Swissgrid's strategic grid 2025. In both panels, 380 kV and 220 kV power lines are displayed in red and green respectively. The proposed upgrades in the strategic grid 2025 are indicated by bold lines. Circles indicate substations and transformers between 220 kV and 380 kV levels are indicated by vertical lines intercepted by two parallel oblique lines – as, e.g., in Mörel, Chamoson or Chippis on the right panel.

at the Zermeiggern power plant of the Mattmark dam.

The right panel of Fig. 3 shows that two extra-high voltage power lines will be added in the Gomsertal from Brig to Ulrichen: a 220 kV line with a capacity of ca. 1 GW and a 380 kV line with a capacity of ca. 1.7 GW. In the strategic grid 2025, one substation connecting Valgrid's 65 kV grid to the 220 kV grid will be moved from Fiesch to nearby Niederernen (still indicated as "Fiesch" in Fig. 3), and another substation in Mörel will connect 380 kV, 220 kV and 65 kV grids. These two substations are obvious choices for connecting the photovoltaic power plant to the extra-high voltage grid and below we consider the two.

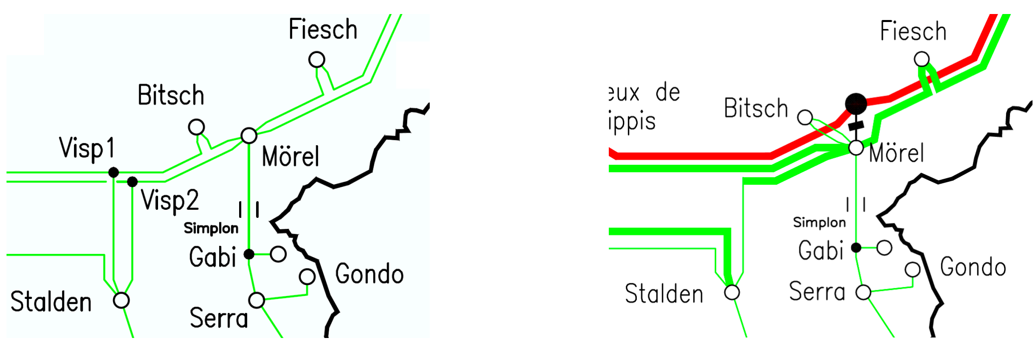

FIG. 3. Local extra-high voltage power lines in the Mörel area as of October 2022 (left panel) and upon completion of Swissgrid's strategic grid 2025 (right panel).

C. Electricity production at extra-high voltage in Valais

To conclude this short general context overview, we note that the proposed Grengiols–Saflischtal photovoltaic farm will be embedded in the electric landscape of Valais. The canton is currently connected to the outside world through 14 extra-high voltage power lines (13 at 220 kV and one at 380 kV), with a total capacity (sum of their power thermal limits) of ca. 7250 MW. Thirteen hydroelectric power plants are connected to the extra-high voltage grid (Châtelard-Vallorcine, Nant-de-Drance, La Batiaz, Fionnay-Mauvoisin, Fionnay-Dixence, Riddes, Bieudron, Nendaz, Bitsch, Stalden, Zermeiggern, Gabi and Gondo), totaling more than 4300 MW of maximal power output. At first glance one may naively conclude that a sufficient transmission capacity already exists for additional productions well above 1 $\mathrm{GW_p}$. One would be wrong for at least four reasons:

• Indigeneous hydroelectric productions may be transferred to the extra-high voltage levels from their lower injection voltage levels. The electric power to be exported may therefore exceed 4300 MW.

• Power transits across Switzerland regularly exceed 3 GW, reaching values as high as 6 GW, mostly from Germany/Austria to Italy. It can be expected that transits regularly reduce the net export capacity out of Valais by 1 GW or more.

• The transmission grid is an infrastructure of strategic importance, whose reliability is based among others on the $N-1$ rule that power supply should not be interrupted by the failure of any one of the grid's components. This translates into unused capacity margins of several tens of percents of the rated capacity for flows on power lines.

• Capacity bottlenecks are often not the power lines themselves, but the transformers that connect them to lower voltage levels and ultimately to consumers. So-called net transfer capacity are standardly significantly lower than the thermal limits of lines.

We therefore consider it important to try and assess whether the extra-high voltage power grid of Switzerland, either in its current configuration, or in the planned, strategic grid 2025 configuration is able to absorb and transmit the power generated in the proposed Grengiols–Saflischtal photovoltaic farm.

D. Our investigations

The first part of this report considers the final, fully implemented strategic grid 2025. Given delays in the completion of that grid, most notably in the construction of the Chippis-Mörel and Airolo-Lavorgo 380 kV lines, we consider in a second part the currently operational swiss extra-high voltage grid.

In both investigations, we have performed a set of 8760 power flow calculations on Swissgrid's strategic grid 2025 embedded into an aggregated model of the European power grid, corresponding to a full year of operation of the European grid, with a granularity of one hour. Production from the Grengiols–Saflischtal power plant has been computed from idaweb/meteosuisse solar radiation data at the nearby Furkapass (similar altitude and same orientation), considering panels tilted at an angle of 72° with respect to the horizontal plane. Our method does not account fully for effects related to bifacial solar panels, and to better connect with the proposed project, we have corrected the production seasonality and increased the power production in winter by 20%. The obtained annual energy production reaches 2 TWh in Section III, with a winter production accounting for 45% of the total annual energy production. Details of the model and further references are given in the Appendix.

III. INJECTION INTO SWISSGRID'S STRATEGIC GRID 2025

A natural choice for injecting large quantities of electric power – on the order of 1 $\mathrm{GW_p}$ or more – into the strategic grid 2025 is the Mörel substation. The right panel of Fig. 3 shows that the injected power can be redistributed over three 220 kV lines and two 380 kV lines. The two voltage levels are further coupled with a 700 MW transformer. Even if one assumes that the two westbound 220 kV lines are used for the Massa/Bitsch and Mattmark/Stalden and Zermeiggern power plants and therefore not available, one is left with 1 GW at 220 kV power capacity to the east in the Gomsertal (with a transformer bottleneck at 700 MW), and $2 \times 1.7\,\mathrm{GW_p}$ at 380 kV, westward to Chippis and eastward to Lavorgo. It seems quite expectable that, at least locally, the grid has a sufficient capacity to accomodate an additional 1 $\mathrm{GW_p}$ injection on the 380 kV level at Mörel substation. The situation would be trickier, would one choose to inject at Fiesch, where the failure of either the eastward or the westward connection may lead to congestions at times of maximal power injection. Given that the distance Saflischtal–Mörel is about the same as the distance Saflischtal–Fiesch, see Fig. 1, we focus on power injection at Mörel from now on.

Fig. 4 shows flows on the 380 kV lines out of Mörel and through the 380 kV/220 kV transformer in Mörel substation for four different weeks in different seasons. Not only did we find no congestion, but the data clearly indicate almost constant capacity margins of more than 1 GW on each 380 kV lines. We checked that these large margins persist even in periods of high hydroelectric productions in Western Valais, with simultaneous maximal injections from Emosson, Nant-de-Drance, Mauvoisin and Grande-Dixence. Furthermore, we have observed no noticeable change in dispatch nor production constraint on hydroelectric productions arising from the new power injection at Mörel. We conclude that Swissgrid's strategic grid 2025 has the capacity to absorb a $1-2\,\mathrm{GW_p}$ production from the proposed Grengiols–Saflischtal photovoltaic farm. This result is not unexpected: it confirms that Swissgrid's strategic grid 2025 has been well calibrated to support the energy transition.

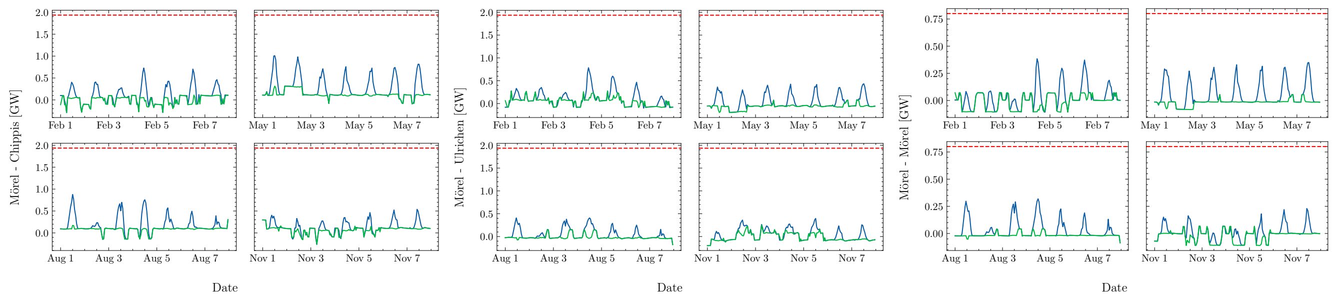

FIG. 4. Power flows on the Mörel-Chippis (four panels on the left) and the Mörel-Ulrichen-Lavorgo (four middle panels) 380 kV lines, and on the Mörel transformer between the 380 kV and 220 kV levels (four panels on the right), in the strategic grid 2025, without (green line) and with (blue) injection of 2 $\mathrm{GW_p}$ at Mörel. Thermal limits are indicated by red dashed lines.

IV. INJECTION INTO SWITZERLAND'S CURRENT EXTRA-HIGH VOLTAGE GRID

Swissgrid's strategic grid 2025 will not be completed before 2028. This is of direct importance for the Grengiols–Saflischtal project, in particular because two of the delayed lines are the Chippis-Mörel 380 kV line (timetable according to Swissgrid's best-case scenario: line commissioning in 2028) and the Airolo-Lavorgo line (timetable according to Swissgrid's best-case scenario: line commissioning in 2026).[2] Accordingly, the transmission capacity out of Mörel will be significantly smaller than with the strategic grid 2025, for at least the next six years. The current local situation around Mörel is shown in the left panel in Fig 3. There are five 220 kV lines connected at Mörel. The westbound lines collect power productions from the Gebidem and Mattmark dams, i.e., the 340 MW Bitsch power plant and the 185 MW Stalden and 74 MW Zermeiggern power plants respectively. In periods of large hydroelectric productions in Valais, with large powers injected from the Grande-Dixence, Mauvoisin, Emosson and Nant-de-Drance plants in western Valais, one expects that the Grengiols–Saflischtal production injected at Mörel would flow dominantly eastward, on the Fiesch-All'Acqua and the Mörel-Handeck lines. Congestions are therefore expected primarily on these lines.

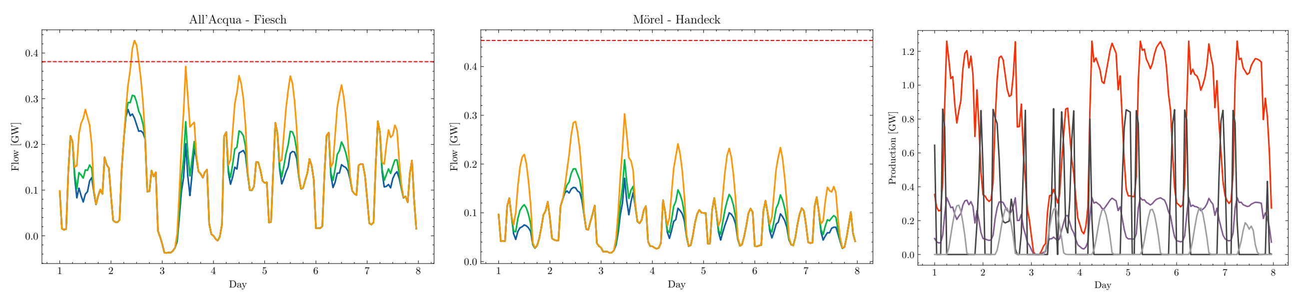

FIG. 5. Simulated week of intense hydroelectric production in Valais. Left: Power flow on the Fiesch-All'Acqua power line. Middle: Power flow on the Mörel-Handeck line. Three levels of power injections from the Grengiols–Saflischtal photovoltaic farm have been considered: 300 $\mathrm{MW_p}$ (blue lines), 500 $\mathrm{MW_p}$ (green) and 1000 $\mathrm{MW_p}$ (orange). Thermal limits are indicated by red dashed lines. Right: Simulated hydroelectric power production from Bieudron (red), Nant-de-Drance (dark grey) and Bitsch (purple) during the week corresponding to the left and middle panels. The power production from the Grengiols–Saflischtal photovoltaic farm, calibrated at 300 $\mathrm{MW_p}$ is shown in light grey.

In Fig. 5 we show flows on the Fiesch-All'Acqua and the Mörel-Handeck 220 kV lines of the current extra-high voltage grid during one typical simulated week of relatively large hydroelectric production. The production profiles of Grande-Dixence, Nant-de-Drance, Massa/Bitsch and the planned Grengiols–Saflischtal plants (the latter calibrated at 300 $\mathrm{MW_p}$) are also shown in that week of large hydroelectric production. The Fiesch-All'Acqua power line is heavily loaded, and the power flow it carries regularly exceeds the thermal limit at times of large photovoltaic injection in Mörel. At that same time, the Mörel-Handeck line, while not too heavily loaded, is within ca. 200 MW of its thermal limit. One clearly expects congestions occuring at least in $N-1$ contingency analysis at these times. We have

[2] See: www.swissgrid.ch/en/home/projects/project-overview.html .

found very regular $N-1$ violations occuring about 20% of the time for a $1000\,\mathrm{MW_p}$ photovoltaic farm in Grengiols–Saflischtal. Bringing the power injection down to $500\,\mathrm{MW_p}$ brings these occurrences down to about 2 % of the time. Finally, we found no $N-1$ violation for power injections of $300\,\mathrm{MW_p}$.

Our approach being based on simulated, and not on historical data, our results should be considered with caution. While we are confident that the total absence of contingencies indicates that a $300\,\mathrm{MW_p}$ injection would be safe, even a low, 2 % level of contingencies may indicate that it would be unsafe to inject $500\,\mathrm{MW_p}$.

V. CONCLUSION

Our results confirm that Swissgrid's strategic grid 2025 is well calibrated to absorb large new renewable power productions. The grid could absorb a large, $1\,\mathrm{GW_p}$ photovoltaic plant like the one proposed at Grengiols–Saflischtal, still with comfortable line capacity margins.

The currently operational transmission grid is however unable to absorb such large power injections. We believe that it could tolerate a peak power injection of about $300\,\mathrm{MW_p}$ but not much more. We see this as the upper limit for power injection from the Grengiols–Salfischtal photovoltaic project until the completion of the strategic grid 2025, including in particular the Chippis-Mörel and Mörel–Lavorgo (via Ulrichen and Airolo) 380 kV lines. These lines will not be completed before 2028 at the earliest, according to Swissgrid. If completion of the project is to occur before that date, its maximal peak power must be smaller than $300\,\mathrm{MW_p}$.

Even a downsized project at $300\,\mathrm{MW_p}$ would require a direct connection to a substation in the extra-high voltage transmission grid. While we did not look into details of the connection line, an extra-high voltage line is in order here: to lower ohmic losses below 1 % of the generated power, even a power line with a low resistance of $R = 0.4\,\Omega$ requires a voltage larger than 110 kV. An alternative coupling not discussed here could be on the existing 65 kV line connecting the 39 MW Heiligkreuz power station to Valgrid's power grid through the Binntal. It is not clear to us if that line can easily be scaled up to 220 kV and 300 MW.

We note that the problematic considered in this report also applies to other similar projects, and that the multiplication of such projects will inevitably raise further issues of grid stability and congestion. When assessing each and every such projects, it has to be kept in mind that Swissgrid's strategic grid 2025 will be completed in 2028 at the earliest. Therefore, power injections in the multi-MW range east of Chippis will be problematic until then.

Further investigations should focus on necessary infrastructures needed to inject the generated electric power into the grid, in particular, (i) details of the connection line to the transmission grid and (ii) converter and other power electronics infrastructures and transformers needed to generate 50 Hz AC electric current at the right voltage level. Last but not least, it seems to be common belief that the production results of Ref. [3] on single photovoltaic panels directly scale up to large plants. This belief seems overly naive to us. One may indeed wonder how much of the expected reduced seasonality, in particular the increased winter production due to the albedo effect on nearby snow-covered surfaces, would persist as more and more of these surfaces are covered by the shade of the photovoltaic panels themselves.

ACKNOWLEDGMENT

We thank Swissgrid for providing relevant data and Nicolas Jordan for useful comments on an earlier version of this report. Work on this report was partly funded by the Swiss National Science Foundation.

APPENDIX: METHODOLOGY

This section is largely inspired from our earlier work, see Ref. [5].

In Refs. [6, 7], we developed a pan-European, aggregated grid model [see Fig. 6 (a)], where different types of production are dispatched following a merit order. As in Ref. [5], we upgrade this model by disaggregating the Swiss power system, and embed the 220 kV and 380 kV transmission grids (the currently operational 2022 grid as of October 2022 and the strategic grid 2025) inside the aggregated European grid [see Fig. 6 (b)]. We shortly describe our model. More details can be found in Refs. [6, 7].

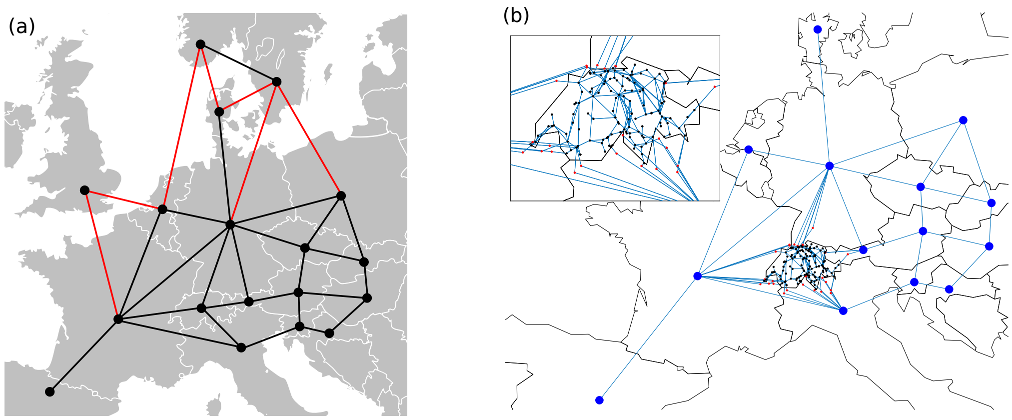

FIG. 6. (a) Aggregated model of the Central and Northern European grid. Each node represents an aggregated dispatch region. Lines represent interconnections: AC connections are in black and DC connections in red. (Figure taken from Ref. [6].) (b) The Swiss high voltage transmission network is embedded into our aggregated model of the pan-European power grid.

Equivalent aggregated models 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. In our case, we are not interested in detailed flows outside Switzerland but still want to account semi-realistically for power flows surrounding Switzerland. Simultaneously, we do not want to rely too heavily on arbitrary dispatches for the geographical distribution of loads within European countries.

A. Aggregated pan-European electric grid

Fig. 6 (a) shows our aggregated European grid, with each node representing an independent dispatch region (Portuguese consumption and production are included in the Spanish node). Aggregated lines have admittances (either for the 2022 grid or the strategic grid 2025) obtained via a standard reduction method [8] and thermal limits are given by the sum of the physical lines they represent. The power flows are computed in the DC lossless approximation [9].

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 (photovoltaic) and wind turbine productions, as well as "miscellaneous productions". RoR is in principle flexible to some extent, but here we choose to neglect curtailment and consider that, as for photovoltaic 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. Each of these productions is characterized by a ramp rate (up/down) which is discussed below.

For each region labelled i and at each time t, we define the residual loads $R_i(t)$ as the difference between the consumption and the non-flexible productions,

$$R_i(t) = L_i(t) - P_i^{\rm inflex}(t), \tag{1}$$

where $L_i(t)$ and $P_i^{\rm inflex}(t)$ give the load and the sum of the non-flexible productions respectively. Our task is to dispatch flexible productions so that their production is equal to the total residual load at all times - this is equivalent to balancing consumption with production.

C. Economic dispatch

A large number of different optimized power flows exist [10–14]. 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. Refs. [6, 7] showed that historical production profiles for all flexible productions in different European countries are well reproduced once these parameters are properly calibrated. To illustrate the validity of our model we present a comparison of historical and calculated hydroelectric production profiles in Norway and Switzerland in Fig. 7. The very good agreement between historical and simulated data for such highly flexible productions as dam hydroelectricity validates our approach.

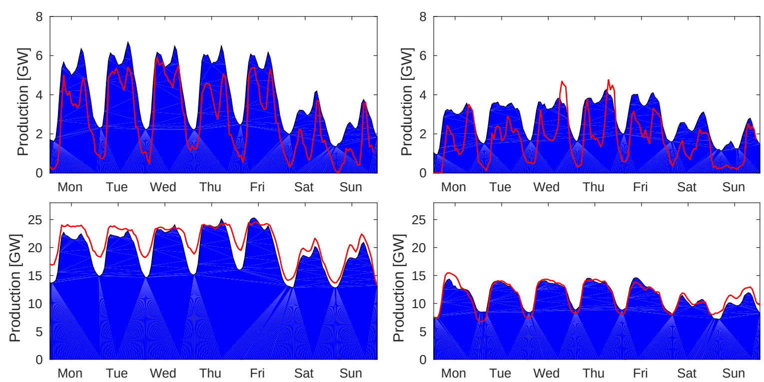

FIG. 7. Dam production of Switzerland (top) and Norway (bottom) for a week in winter (left) and summer (right) in 2015. Dispatched productions are displayed in blue and actual 2015 production profiles are in red.

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

$$W_i(t) = \sum_k \left[a^k P_i^k(t) + b^k \frac{P_i^k(t)^2}{P_{\max i}^k} \right] \Delta t, \tag{2}$$

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

$$W(\{P_i^k(t)\}) = \sum_{i,t} W_i(t), \tag{3}$$

under the following technical constraints:

a. Power limits $P_i^k(t) \le P_{\max i}^k$, $\forall t$; the power generated never exceeds its maximal installed capacity.

b. Ramp rates $|\partial P_i^k(t)/\partial t| \leq \Gamma_i^k$, $\forall t$; each production type has a maximal ramp rate Γ_i^k 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 $|F_k(t)| \leq F_k^{\max}$; they should never exceed the thermal limit $F_k^{\max}$ between regions.

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

The pumped-storage (PS) plants have no marginal cost. The price of electricity gives them the signal whether they must pump or generate and its variations allows them to generate profits. We showed that the residual load, defined in Eq. (1), is strongly correlated to the day-ahead electricity price [15]. Consequenty, one can define an effective electricity price $p_{\mathrm{eff}\,i}(t)$ based on the residual load. In the ith region, the revenues $G_{\mathrm{PS}\,i}$ generated by the PS plants in this region depend on their pump/turbine powers $P_{\mathrm{p}i}(t)$ and $P_{\mathrm{t}i}(t)$ and the filling $S_{\mathrm{PS}_i}(t)$ of their reservoirs as

$$G_{\mathrm{PS}\,i} = \sum_k p_{\mathrm{eff}\,i}(t_k)[P_{\mathrm{t}_i}(t_k) - P_{\mathrm{p}_i}(t_k)]\Delta t \tag{4}$$

$$\text{s.t. } 0 \leq S_{\mathrm{PS}_i}(t_k) \leq S_{\mathrm{PS}i}^{\max} \quad , \forall k \, . \tag{5}$$

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

$$S_{\mathrm{PS}_i}(t + \Delta t) = S_{\mathrm{PS}_i}(t) + [\eta P_{\mathrm{p}_i}(t) - \eta^{-1} P_{\mathrm{t}_i}(t)]\Delta t \, , \tag{6}$$

with a typical pump/turbine efficiency of $\eta = 0.9$ (each way). We define a cost function for PS operations as

$$W_{\mathrm{PS}} = -\sum_i G_{\mathrm{PS}\,i} \, . \tag{7}$$

We add this term to the cost function defined in Eq. (3), after which our economic dispatch minimizes the total production cost while maximizing the revenues of the PS plants.

D. Disaggregation of Switzerland

Effective admittances are determined for lines between Swiss buses and the aggregated European buses. They are chosen so that, with historical power injections in Switzerland and Europe, numerically obtained power flows on these lines are close to the corresponding historical power flows. Fig. 8 illustrates how well this calibration process works.

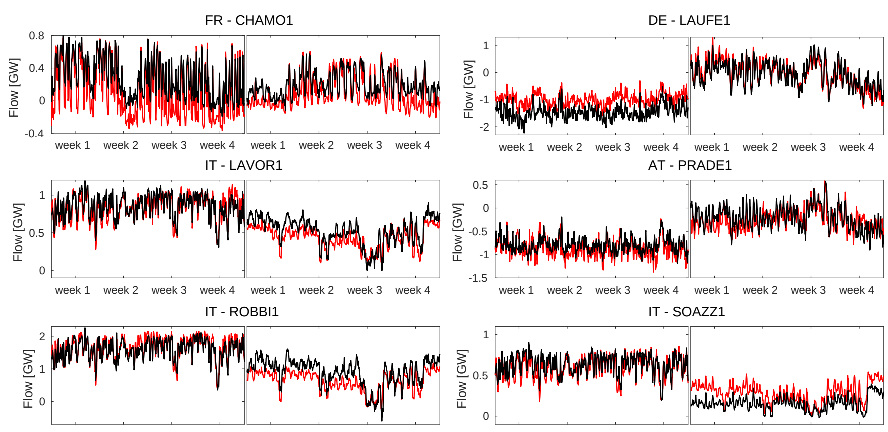

FIG. 8. Calculated (red) vs. historical (black) power flows on six different interconnections to Switzerland for four winter (left panels) and four summer weeks (right panels) in 2015.

For lines inside Switzerland, we use their true admittances. Our economic dispatch determines the total production for each production type. The power flow computations require geographical resolution, i.e., power injections at each bus, which we obtain as follows. For a given production type, labelled k, the rated power connected to the grid bus number i is given by $P^k_{\text{rated}\,i}$. The distribution factor π_i^k is defined as

$$\pi_i^k = \frac{P^k_{\text{rated}\,i}}{P^k_{\text{rated CH}}}\,, \tag{8}$$

where $P^k_{\text{rated CH}}$ is the Swiss nameplate capacity of this type of production. Then, the power injection $\Pi_i(t)$ in the ith bus is given by

$$\Pi_i(t) = \sum_k \pi_i^k P^k_{\text{CH}}(t) - R_i(t)\,. \tag{9}$$

Here, $R_i(t)$ is the residual load at bus number i, defined as the difference between the true 2015 load and the numerically modeled RES productions. More information on the model, its calibration and validation can be found in Ref. [6].

The very good to excellent agreement between simulated and historical data, for dam hydroelectric productions in Switzerland and Norway, see Fig. 7, as well as for the power flows on international lines connecting Switzerland to Europe, see Fig. 8 fully validate our model.

---

[1] D. Biner, "Solar-Fieber im Oberwallis: Ein neues Projekt stellt Gondo und Grengiols in den Schatten," *NZZ, 08.10.2022.*
[2] N. Benelli, "Gigantisches Solarprojekt in Grengiols stellt alles in den Schatten," *Walliser Bote, 14.04.2022.*
[3] J. Rohrer, "Ist Photovoltaik in den Alpen sinnvoll?," *Bulletin Électrosuisse*, 2012.
[4] "List of photovoltaic power stations," *https://en.wikipedia.org/wiki/List_of_photovoltaic_power_stations; consulted October 13, 2022.*
[5] L. Pagnier and P. Jacquod, "Swissgrid's strategic grid 2025 : an independent analysis," *(available upon request)*, 2018.
[6] L. Pagnier and P. Jacquod, "A predictive pan-european economic and production dispatch model for the energy transition in the electricity sector," in *PowerTech, 2017 IEEE Manchester*, IEEE, 2017.
[7] P. Jacquod and L. Pagnier, "Le paradoxe de la transition énergétique," *Bulletin Électrosuisse*, 2017.
[8] 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.
[9] A. Gómez-Expósito, A. J. Conejo, and C. Cañizares, *Electric energy systems: analysis and operation.* CRC Press, 2008.
[10] G. Czisch, *Szenarien zur zukünftigen Stromversorgung: kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien.* PhD thesis, 2005.
[11] 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.
[12] F. Comaty, A. Ulbig, and G. Andersson, "Ist das geplante Stromsystem der Schweiz für die Umsetzung der Energiestrategie 2050 aus technischer Sicht geeignet?," 2014.
[13] 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.
[14] J. Schwippe, A. Seack, and C. Rehtanz, "Pan-european market and network simulation model," in *PowerTech (POWERTECH), 2013 IEEE Grenoble*, pp. 1–6, IEEE, 2013.
[15] L. Pagnier and P. Jacquod, "How fast can one overcome the paradox of the energy transition? a predictive physico-economic model for the european power grid," *Energy*, vol. 157, pp. 550–560, 2017.