The bright side of PV production in snow-covered mountains

Annelen Kahl[a,b,1], Jérôme Dujardin[a], and Michael Lehning[a,b]

[a]School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland; and [b]Snow and Permafrost/Snow Processes, WSL Institute for Snow and Avalanche Research (SLF), 7260 Davos, Switzerland

Edited by Thomas E. Mallouk, The Pennsylvania State University, University Park, PA, and approved November 28, 2018 (received for review January 9, 2018)

Our work explores the prospect of bringing the temporal production profile of solar photovoltaics (PV) into better correlation with typical electricity consumption patterns in the midlatitudes. To do so, we quantify the potential of three choices for PV installations that increase production during the winter months when electricity is most needed. These are placements that favor (*i*) high winter irradiance, (*ii*) high ground-reflected radiation, and (*iii*) steeper-than-usual panel tilt angles. In addition to spatial estimates of the production potential, we compare the performance of different PV placement scenarios in urban and mountain environments for the country of Switzerland. The results show that the energy deficit in a future fully renewable production from wind power, hydropower, and geothermal power could be significantly reduced when solar PV is installed at high elevations. Because the temporal production patterns match the typical demand more closely than the production in urban environments, electricity production could be shifted from summer to winter without reducing the annual total production. Such mountain installations require significantly less surface area and, combined with steeper panel tilt angles, up to 50% of the winter deficit in electricity production can be mediated.

renewable energy | photovoltaic | surface reflectance | seasonal energy gap | panel tilt

In a world that needs to transition to a low-carbon energy production, solar photovoltaic (PV) technology has become a VIP member. It is easy to install, has a low impact on its surroundings, and is increasingly more affordable and its fuel is freely available at any location on the surface of the planet. Despite these positive properties, lower sun angles and significant cloud cover in temperate zones result in a seasonal production pattern that is anticorrelated with demand. Specifically, PV production is high in summer and low in winter when it is most needed. This complicates the proliferation of PV technology in future energy markets (1, 2). Consequently, significant research has addressed this problem. The first category of proposed solutions consists of studying the mix of solar with other renewable technologies, to find combinations with more suitable production patterns. Wind has often been selected in combination with PV because in many regions wind speeds are higher in winter, offsetting the lower winter PV production. Previous studies have estimated the optimal mixing ratio of wind and solar production for different countries and set upper limits for the contribution of PV to a renewable energy mix that would still allow for a balanced production (3–6). Hydropower can under certain conditions also provide a viable complement (7). A second approach is the development or extension of seasonal storage; here, of course, the role of storage hydropower is paramount, as it represents the only existing technology that can fulfill this function at a large scale (8). Finally, spatial dispersion of production, or rather interconnection through a highly developed transmission network that links places of different production and demand patterns, could be considered a mitigation strategy (9, 10). While of some significance to the seasonal energy gap, the proposed solutions mentioned above are more readily applicable to short-term mismatches between supply and demand. Ultimately, none of them sufficiently alleviates the undesirable desynchronization of PV production with demand; they simply attempt to accommodate it.

We present an alternative approach of modifying the seasonal timing of PV production such that it is more in sync with demand. In a future fully renewable energy mix with high percentages of variable and intermittent sources and with neighboring countries that are subject to similar constraints, electricity produced at the right moment will become very valuable. Maximum annual production of energy through the use of south-facing PV panels may be ineffective if that energy cannot be stored easily and cheaply. Options that promote an energy profile that matches demands are needed and our research explores an innovative solution to this problem, using existing PV technology.

Systematic Analysis of Three Measures That Increase Winter Production

Our work is applied to Switzerland, but the methods and results presented can be transferred to other midlatitude mountainous regions with similar solar and cloud conditions. We analyze the following three controls on winter PV production: (*i*) an increase in incoming irradiance during the winter through strategic placement of PV panels in locations with minimal winter cloud cover, (*ii*) Increased ground reflectance through improved placement of PV panels in zones with extended periods of snow cover, and (*iii*) increased panel tilt to favor winter production by better aligning to low sun angles. We quantify the impacts of these three measures on the temporal production patterns in two ways. First,

Significance

Our work shows that it is possible to turn solar photovoltaics (PV) into a more reliable and better-suited contributor to a future renewable energy mix. The correct placement and orientation of solar panels in mountain areas shift a significant amount of electricity generation from the summer to the winter months. PV technology is economically and technologically very promising. Bringing the production pattern closer to typical consumption patterns in the midlatitudes represents an important step toward higher penetration of PV technology on future energy markets. Moreover, a reduction of the winter energy gap by placing PV on (existing) mountain infrastructure lowers the need for (unrealistic) additional storage.

Author contributions: A.K. and M.L. designed research; A.K. performed research; A.K. contributed new reagents/analytic tools; A.K. and J.D. analyzed data; J.D. developed and ran the computations of imbalance between renewable production sources aside from PV; and A.K., J.D., and M.L. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence should be addressed. Email: annelen.kahl@epfl.ch.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1720808116/-/DCSupplemental.

Published online January 7, 2019.

we systematically analyze the environmental conditions for all of Switzerland, using spatially distributed irradiance, snow cover duration, and albedo values derived from satellite imagery. Second, we model specific PV placement scenarios to visualize how the temporal behavior of electricity production differs for PV installations in urban areas and in the mountains. Finally, we analyze the impact of location and of panel geometry on the national electricity budget, showing how a shift in the annual production profile reduces the mismatch between demand and production and thus lowers the need for other balancing measures.

Irradiance. The average yearly irradiance for Switzerland varies from 130 W/m^2 in the North to almost 200 W/m^2 in the mountainous South (Fig. 1*A*). Irradiance in the absence of clouds is larger at high elevations because the overlying atmosphere is thinner so it absorbs less. In addition to the general trend caused by atmospheric thickness, mountains are advantageous in winter because persistent low-level stratus clouds and fog are confined to the valleys. The scatterplot (Fig. 1*B*) shows the elevation dependence of annual total irradiance, as well as the increased gradient during the winter period.

Snow Cover Duration. Snow cover duration (SCD) (Fig. 2*A*) is closely correlated with elevation and thus varies strongly throughout Switzerland. At the highest elevations, snow is present almost all year long, while the lowest pixels are completely snow-free. At 2,000 m elevation, an average of 190 snow days per year was recorded during our study period from 2011 to 2016. The relative spatial patterns are very similar to those of the irradiance (Fig. 1*A*).

Panel Tilt. In addition to the two environmental drivers, irradiance and SCD, panel tilt is a more technical dial on PV production. While the azimuth angle of the panel mostly impacts the production profile throughout the day, it is the panel tilt that determines during which season the electricity production is optimal. Assuming permanently clear skies and constant atmospheric conditions in terms of aerosol concentration and humidity, the optimal panel tilt would simply be a function of latitude and time of the year. In midlatitudes, however, cloud cover plays an important role since it attenuates incoming shortwave radiation and changes the ratio of diffuse to direct radiation (11–13). When the panel tilt and orientation cannot be adjusted throughout the year, it is common practice to install south-facing PV panels with a tilt that generates a maximum annual production irrespective of its timing and without considering the presence of snow which reflects considerable amounts of solar radiation. Fig. 3 shows modeled annual production as function of tilt for an example location at 2,500 m. The red line shows the annual production for a constant surface reflectance of 20%, while the blue line uses a satellite-derived albedo time series to accurately capture the changes in reflectance due to the presence of snow. Thus, Fig. 3 contrasts identical incoming irradiance for snow-free and snow-covered locations. Total production vs. winter production differs by location, depending on topography, but the fundamental properties related to tilt angle are the same everywhere. The optimal tilt considering snow $tilt^{s}_{ref}$ is steeper than without considering snow $tilt^{ns}_{ref}$. This is due to the increase in winter production shown in Fig. 3, *Bottom Left*. Winter production continues to increase toward steeper tilts, even after annual total production begins to drop. When we compare $tilt^{ns}_{ref}$ with the blue curve (which accounts for snow albedo), we can see that we could install panels in a snowy environment at an angle as steep as $tilt_{max}$ without compromising the total annual production with respect to the snow-free case. Or, expressed differently, we can shift production from summer to winter without decreasing the annual total production simply by choosing a snowy location in combination with a steeper panel tilt.

The difference between these two situations, with equal annual total but very different winter production, is illustrated in Fig. 3, *Right*. The angle difference $tilt_{max} - tilt^{ns}_{ref}$ varies from zero in places without snow cover to almost 30° at high elevations (Fig. 3, *Top Right*) and the corresponding increase in winter

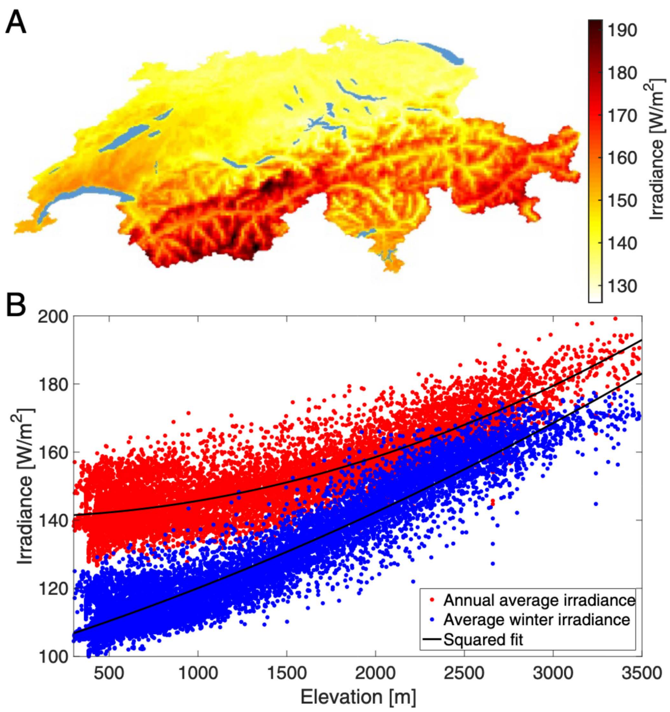

Fig. 1. Distribution of incoming global irradiance throughout Switzerland, 2011–2016. (*A*) Spatial distribution of average irradiance. (*B*) Elevation dependence of all-year average and of winter-only average irradiance (January–May, November–December).

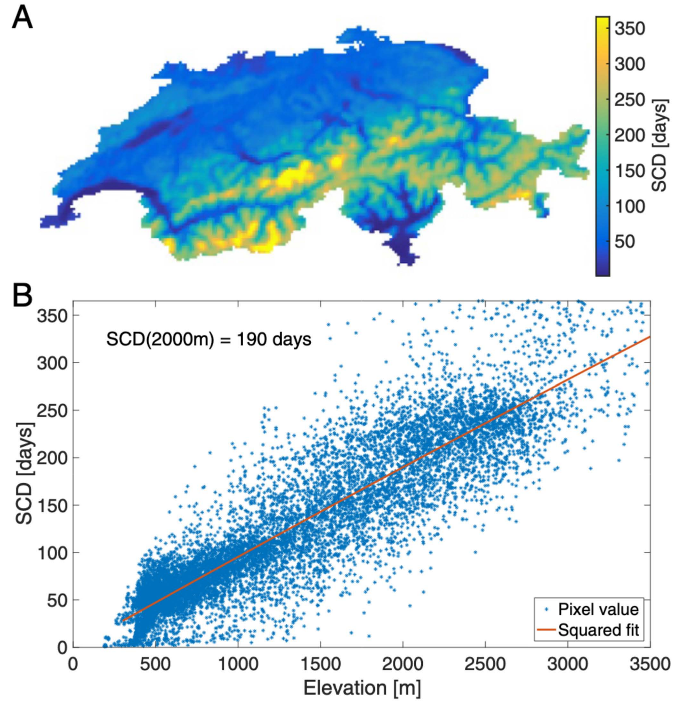

Fig. 2. Distribution of average SCD throughout Switzerland, 2011–2016. (*A*) Spatial distribution of SCD. (*B*) Elevation dependence of 6-y mean annual SCD (one point per pixel in *A*).

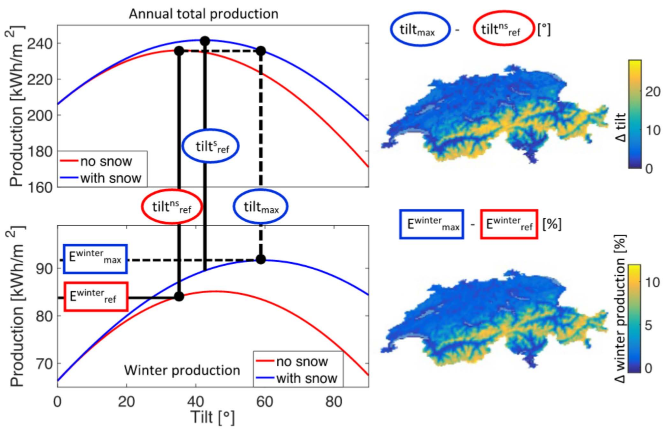

Fig. 3. Illustration of how panel tilt shifts the electricity production toward the winter months. (*Left*) Annual total production (*Top*) and winter production (*Bottom*) as a function of panel tilt for an example location at 2,500 m elevation, modeled for snow-free (red) and snow-covered (blue) conditions. (*Right*) Comparison of snow-covered and snow-free conditions with equal annual total, but increased winter production for the snow-covered scenario. (*Top Right*) Increase in tilt when taking into account snow. (*Bottom Right*) Corresponding increase in winter production.

production can be as high as 12% (Fig. 3, *Bottom Right*). In about 10% of the country's area even higher winter production could be reached at tilt angles beyond $tilt_{max}$; this, however, would be at the cost of decreasing the annual total production.

In Switzerland rooftop installations are constrained to the angle of the roof and we can see from our validation study (*SI Appendix*) that shallow angles are more prone to production loss through snow cover on the panels. Installations at high elevations experience more frequent snowfall and hence might also suffer a certain production loss. However, in the scenario we present below we assume vertical panels, which rarely accumulate snow and would shed it very quickly. Weighing the advantage of higher theoretical production values at 65° tilt against a likelihood of having a cleaner panel at 90° tilt would need to be done on a case-by-case basis because it requires site-specific information regarding snow, dust, and wind.

Scenario Approach

In the following, we move from the quantification of the drivers to the quantification of electricity production for different installation scenarios of PV panels throughout Switzerland. In those scenarios (specified in *Methods*), the total surface area of installed PV panels is chosen such that the resulting country-wide production always equals 12 TWh/y. This amount would replace half of the current nuclear production, which will be removed in its entirety from the country's future energy portfolio (14). We computed the required surface area for each year of our study period 2011–2016, as well as the corresponding production during the winter months.

Comparison of PV Surface Area and Production. Fig. 4 illustrates the impact and relative importance of the three driving factors for increased winter PV production: (*i*) irradiance, represented by the difference between the urban and the mountain no-snow scenario (red and green lines); (*ii*) ground reflectance, characterized by the difference between the two mountain scenarios (green and blue lines); and (*iii*) panel tilt, as an independent variable on the *x* axis.

There is a large difference between the urban and the mountain scenarios in terms of the surface area that is required to produce 12 TWh/y (Fig. 4*A*). At all tilts, this difference amounts to over 20%, which corresponds to more than $10\,\mathrm{km}^2$ or over 1,000 soccer fields. The difference is dominated by the effect of location, i.e., the difference in received irradiance. The additional effect of ground reflectance becomes increasingly stronger for steep tilt angles which orient the panels toward the ground. At vertical installation, the presence of snow results in a 13% decrease in required PV surface, which can be added to the reduction due to location. The shape of dependence of the required surface area on the panel tilt is very similar for the urban and mountain no-snow scenarios: Minima are reached around 37°. The mountain snow scenario reaches optimal productivity at a steeper tilt of 43° due to the presence of snow, which boosts the productivity in winter. The winter productivity per surface area (Fig. 4*B*) also displays a very similar tilt dependence for the urban and mountain no-snow scenarios, but with a difference in production of 6.2−9.2 $\mathrm{W/m^2}$ that corresponds to ∼50%. The ∼50%. The increase in winter production due to snow cover is small at first, but increases to 5.1 $\mathrm{W/m^2}$ at steep tilt angles. Toward high tilt angles it is the presence of snow alone that continues to raise the winter production. While the other two scenarios show a decrease in winter productivity beyond 52°, the snow scenario continues to improve up to 65°.

To be even more specific than lumped seasonal productivity, Fig. 5 shows the smoothed production profile for the three scenarios at specific tilt angles. We contrast urban production at the conventional tilt of 40° with mountain production at the extreme angle of 90°. The corresponding required surface areas of PV panels are given in *SI Appendix*, Table S4.

Now the full extent of the shift in seasonal production becomes apparent. While the urban scenario persistently peaks during the summer months, the mountain scenarios follow exactly the opposite trend: High power values in winter and lower ones in summer. The corresponding differences in production profile, shown in Fig. 5*B*, briefly exceed 150% in midwinter and reaches almost 50% in midsummer. We choose to model vertical panels

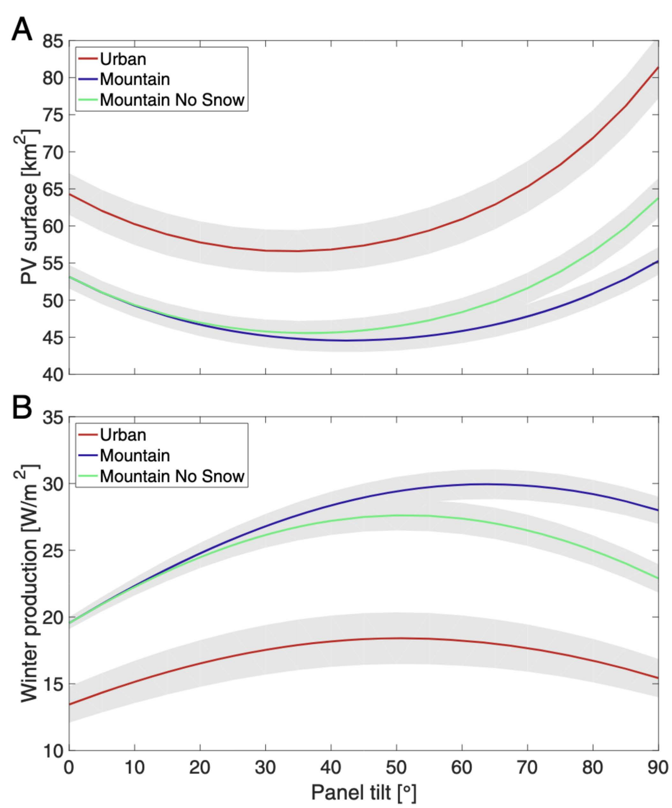

Fig. 4. (*A* and *B*) Tilt dependences for the three PV scenarios (2011–2016), average (lines) and SD (gray shading) of (*A*) required surface area to produce 12 TWh/y and (*B*) winter production per unit surface area.

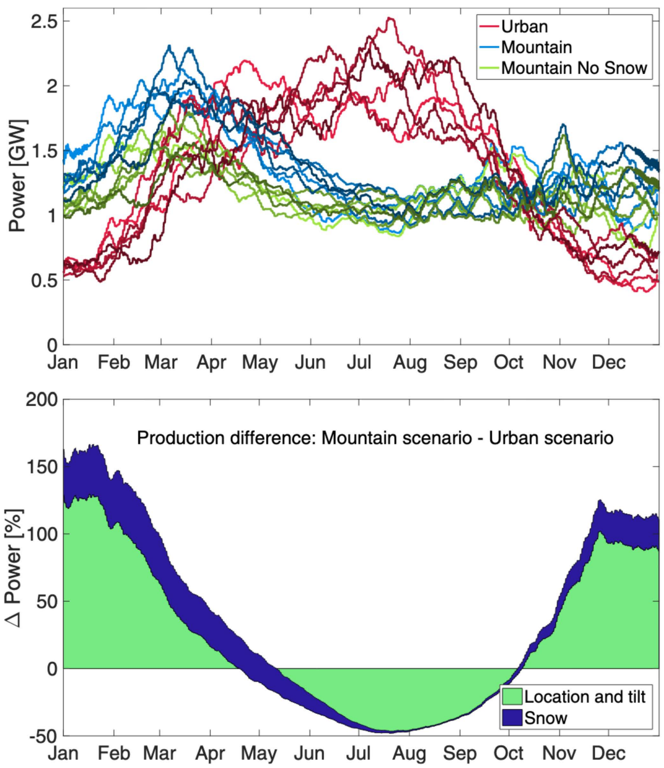

Fig. 5. Production profiles for the three PV scenarios at specific tilt angles. Tilt and surface area are as specified in *SI Appendix*, Table S4. (*A*) Yearly profiles for 2011–2016 (increasing darkness), with 30-d moving mean filter applied to smoothen hourly values. (*B*) Difference in electricity production between urban and mountain scenarios (%), 6-y average of profiles in *A*. Green area: portion of difference due to location and tilt. Blue area: contribution of snow cover.

for their ease of installation on walls and the fact that snow easily slides off. Note in *SI Appendix*, Table S4 that installations at 65° tilt would be even more efficient because the same power can be produced over a smaller panel surface.

Comparison of Impacts on a Fully Renewable, Swiss Electricty System. How would this shift in PV production affect the electricity system of a future renewable Switzerland? First, to get an estimate, we look at the annual profile of demand and of all contributing production time series and compute the residual demand that could not be satisfied. This production includes the generation from hydropower in 2014 and the PV production for the urban and the mountain scenario, as well as a small geothermal baseload and some generation from wind turbines, both corresponding to the Swiss Energy Strategy 2050 targets. The mismatch between demand and production illustrated in Fig. 6 underscores the remarkable impact of moving PV production from urban to mountain environments: The seasonal energy gap is reduced to half. In addition, we ran the power and energy balance model described in *Methods* to compare the 2014 residual imbalance that would arise from the different PV scenarios after having used pumped storage and storage hydropower plants in the most efficient manner. In 2014 with nuclear production this imbalance amounted to 3.5 TWh. For the urban scenario, which shows the largest winter deficit, the imbalance is the highest, reaching 4.8 TWh when the standard 40° tilt is used and 3.7 TWh when the winter-productive 90° tilt is used. For the mountain scenarios, the imbalance lies between 4 TWh and 2.6 TWh (for tilts of 35° and 90°, respectively). Those numbers convey two important messages: First, the flexibility of storage hydropower is never sufficient to completely alleviate the imbalance between production and demand, and second, the national strategy of PV placement plays an important role in the management of the seasonal imbalance.

Conclusions and Outlook

We have shown that high-elevation PV installations are favorable to alleviate the winter energy gap in the supply of renewable electricity in Switzerland. A general trend of increasing radiation toward higher elevation is due to a thinner atmosphere and the absence of fog in winter. In addition, the presence of snow with its high surface reflectance will increase the yield of PV panels when optimal tilt angles are used. We show a quantitative assessment of the effect of snow. Snow can increase local yield by 10%. Our analysis presents an important step in the detailed planning of renewable energy installations for mountainous countries, because it shows—using Switzerland as an example—how to best exploit the natural environment for an optimal siting of PV installations. Placing PV installations at sufficiently high elevation and taking advantage of a snow-covered ground can replace nuclear power production more efficiently than installations in urban centers. Compared with installing PV in urban areas, less surface area for PV installations is needed, and combined with steeper PV tilt angles, up to 50% of the Swiss winter production gap can be alleviated. Additionally, steeper installation angles are also preferable for installations on existing infrastructure and for optimal self-removal of snow through sliding. Finally, steeper panels will suffer less from soiling due to dust, dirt, and other particles (15, 16). To allow for a clear interpretation of the results presented here, we address the current limits of our model and outline future improvements. We acknowledge that our PV model is very simplistic concerning technical/electrical components of the production. This paper focuses on the spatial and temporal variability of radiation inputs to PV production to illustrate their relative differences and the importance of choice in location. It does not claim to accurately simulate the electricity production for one particular panel type and grid connection in one specific location. However, we do want to stress that we have chosen the model simplifications such that they either are independent of geographic region or otherwise allow uncertainty that would only strengthen our results if removed. Our analysis is therefore conservative in many aspects. Possible improvements in the analysis include the following: (*i*) The important forward-scattering properties of snow reflectance would increase total irradiance on PV panels. (*ii*) Temperature effects would improve the performance of PV in winter and for

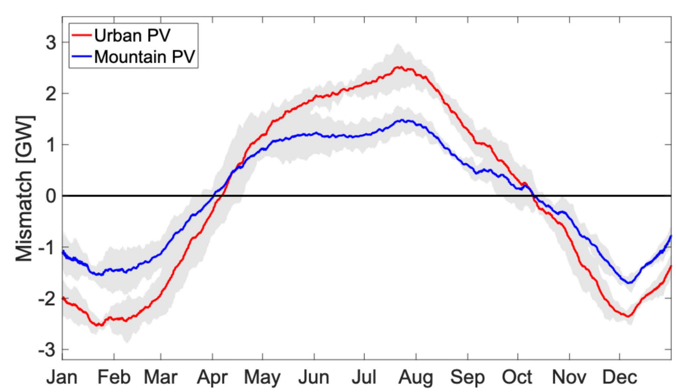

Fig. 6. Temporal behavior of mismatch between fully renewable electricity production and demand in Switzerland throughout the year for the urban scenario (red) at 40° and the mountain scenario (blue) at 90°, 4-y average (2011–2014), smoothed using a 30-d moving mean filter. The current nuclear production is replaced by a mix of solar PV, wind power, and geothermal power.

ENVIRONMENTAL SCIENCES
SUSTAINABILITY SCIENCE

cold regions. (*iii*) Tilt adjustments during the year: For rooftop installations tilt adjustments are not practical or often not permitted. For installations in the mountains, this may be possible; e.g., there are current installation plans for a combination of PV panels with existing avalanche defense structures. These plans include mechanical tilt adjustment. (*iv*) The effect of tilt on soiling and snow removal: The steeper the panels are, the cleaner they stay. (*v*) Topographic shading effects at high spatial resolution: Although terrain shading is accounted for through local horizons, its accuracy is limited by the spatial resolution of the satellite-derived radiation product.

Beyond technical aspects, other uncertainties might affect the success of PV installations in mountainous areas: (*i*) Future warming will likely decrease the duration of highly reflective snow cover at mid- and eventually at high elevations. The mountain no-snow scenario represents the upper limit of this effect in our study and shows that even without any snow a significant advantage of the mountainous location remains due to cloud/fog effects. (*ii*) High-altitude locations are often less accessible than our rooftops and might not have a direct grid connection. However, countries within the Alpine arc possess an impressive network of access roads into high terrain and the abundance of hydropower installations provides a good infrastructural base. (*iii*) Social acceptance of renewable energy installations varies strongly with time and geographic region. The need for unbiased, fact-based information for the broad public is crucial before any further decisions should be made. While those last two points are very important, they are subject to change and dependent on human values and priorities as well as on political decisions. Their assessment is hence beyond the scope of our paper and we refer readers to other studies (17, 18). It is our aim with this paper to bring to attention the considerable physical potential of high-elevation locations that could be harvested by solar PV installations at a favorable seasonal rhythm.

Methods

PV Production Calculated with the SUNWELL Model. The total amount of shortwave radiation that vertically impinges on a PV panel of given orientation and tilt and the resulting electricity production are calculated using our PV model SUNWELL. It computes the panel-normal components of the three contributions, direct beam radiation, sky diffuse radiation, and ground-reflected radiation, and converts them into electricity output by applying an overall system efficiency (see *SI Appendix* for details). Inputs to SUNWELL are the global surface incoming shortwave radiation (SIS) and the direct surface incoming shortwave radiation (SISDIR) (19), provided by MeteoSwiss. They are derived from Meteosat imagery (20) using the HelioMont (19) algorithm and provide spatially explicit information at an hourly resolution of the global and direct beam radiation that reaches the surface of the Earth. HelioMont accounts for cloud cover and other atmospheric effects, as well as for terrain shading. At the resolution of 1.25° min, pixels will often be a combination of shaded and nonshaded zones. This also means that the pixel average irradiance, which we use in our simulation, will always be equal to or lower than the maximum value and better subpixel location that could be found. Despite these simplifications, the validation presented in *SI Appendix* shows that SUNWELL faithfully reproduces the seasonal trends in real production for a number of sites. The portion of the solar radiation that reaches the panel via reflection from the ground is a function of surface albedo, which varies strongly with the presence of snow cover. To capture this difference, we use at all times the albedo product called MSG.ALB (19), which is derived from imagery of Meteosat Second Generation satellites.

PV Placement Scenarios. The spectrum of possible designs for PV placement scenarios spans from the conventional rooftop installation in urban and industrial zones to innovative designs as PV farms or on existing infrastructure in mountainous terrain. The production profile of any realistic, future solution will probably lie somewhere in between. Hence we chose these two framing scenarios for our analysis. We apply different ranking criteria to select among the candidate pixels and impose a maximum allowed cover fraction to each selected pixel to avoid placing an unrealistically large amount of PV surface in any single pixel. This cover fraction is determined by the pixel's land surface cover type, as given by the CORINE dataset (21), and

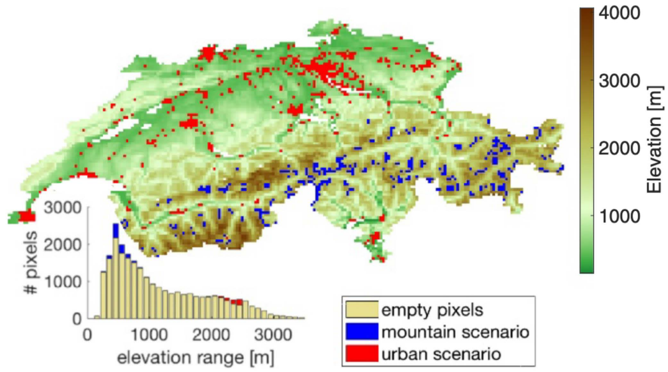

Fig. 7. Spatial distribution of PV panels for two different installation scenarios in urban and mountain environments. Shown is a digital elevation model of Switzerland (Shuttle Radar Topography Mission, ref. 23), with PV placements for urban scenario (red) and mountain scenario (blue). (*Inset*) Histogram of elevation distribution of scenario pixels.

varies between 0% and 5% (*SI Appendix*). For the urban scenario, we rank all pixels by their population density (22) and then fill them with PV until the maximum cover fraction is reached. For the mountain scenario, pixels are ranked by their winter productivity. In addition, an elevation limit of 2,500 m prohibits installations at unreasonably high and inaccessible places. Fig. 7 shows the spatial distribution of PV placements for the two scenarios as well as their statistical distribution of elevation range (Fig. 7, *Inset*).

The urban scenario covers all major cities in the North and reaches even some of the smaller towns in the southern part of the country. All chosen pixels are located at low elevations between 200 m and 600 m. The criterion of high winter production exclusively selects pixels at high elevations just below the limit of 2,500 m in the southern part of the country. The difference in production between these two scenarios is a combination of the difference in weather and the difference in ground reflectance due to snow cover. To clearly separate those two components, we also ran the mountain scenario without snow, by maintaining a constant surface reflectance of 20% throughout the year. We refer to this scenario as the "mountain no snow" scenario. Its primary purpose is to isolate the effect of snow cover on PV productivity, but simultaneously it serves as a simplified and extreme preview on the impact of climate change. With warming temperatures, the presence of snow will slowly decrease and with it the beneficial increase in ground reflectance.

Power and Energy Balance Model to Compute the Residual Seasonal Energy Imbalance. The Renewable Electricity Model for Evolving Distributed Infrastructure (REMEDI) is described in detail in ref. 3. It has been designed to estimate how much mismatch between electricity consumption and production from nondispatchable sources could be alleviated by an optimal use of the Swiss hydropower facilities. To do so, it uses the real time series of hourly national electricity demand (24), the PV production corresponding to the three scenarios described above, a synthetic wind production time series based on real wind measurements (25), a small geothermal base load, and the real monthly production values from the run-of-river power plants (14). Those time series are depicted in *SI Appendix*, Fig. S4. When all those contributions are added together, the storage hydropower facilities (26) are invoked to counterbalance the resulting mismatch within their capacities. Real time series of the production from storage hydropower (14) and of the reservoirs' level (27) allowed the retrieval of the energy-equivalent inflow into the system (shown in *SI Appendix*, Fig. S4). Thus, storage hydropower is used in an energetically optimal way which considers the limited size of the reservoirs and the temporal behavior of the demand of the other nondispatchable sources and of the water inflow. Ultimately, this model provides how much energy could not be transferred from the summer period, with its high production and low demand, to the winter, with the opposite trend. Eventually, in a fully renewable Switzerland this amount of energy would have to be taken care of through supplementary seasonal storage or import from and export to the neighboring countries.

ACKNOWLEDGMENTS. We thank the three anonymous reviewers for their insightful comments. MeteoSwiss provided the HelioMont radiation product and Reto Stöckli gave helpful advice on its use and background. Valuable information came from Bert Kruyt who contributed wind energy production data. Romande Energie and Elektrizitätswerke Davos granted access to PV production data. We further acknowledge interesting discussions with the Zurich University of Applied Sciences (Jürg Rohrer) and the Energiewerke Kanton Zürich. This work was funded by Innosuisse through the Swiss Competence Center for Energy Research, Supply of Energy and the Swiss National Science Foundation.

1. Sivaram V, Kann S (2016) Solar power needs a more ambitious cost target. *Nat Energy* 1:16036.
2. Creutzig F, et al. (2017) The underestimated potential of solar energy to mitigate climate change. *Nat Energy* 2:17140.
3. Dujardin J, Kahl A, Kruyt B, Bartlett S, Lehning M (2017) Interplay between photovoltaic, wind energy and storage hydropower in a fully renewable Switzerland. *Energy* 135:513–525.
4. Bett PE, Thornton HE (2016) The climatological relationships between wind and solar energy supply in Britain. *Renewable Energy* 87:96–110.
5. Monforti F, et al. (2014) Assessing complementarity of wind and solar resources for energy production in Italy. A Monte Carlo approach. *Renewable Energy* 63:576–586.
6. Hoicka CE, Rowlands IH (2011) Solar and wind resource complementarity: Advancing options for renewable electricity integration in Ontario, Canada. *Renewable Energy* 36:97–107.
7. François B, Hingray B, Raynaud D, Borga M, Creutin JD (2016) Increasing climate-related-energy penetration by integrating run-of-the river hydropower to wind/solar mix. *Renewable Energy* 87:686–696.
8. Ess F, Haefke L, Hobohm J, Peter F, Wünsch M (2012) The significance of international hydropower storage for the energy transition (Prognos AG, Basel, Switzerland), Technical Report 27447.
9. Denholm P, Hand M (2011) Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. *Energy Policy* 39:1817–1830.
10. Becker S, Rodriguez RA, Andresen GB, Schramm S, Greiner M (2014) Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply. *Energy* 64:404–418.
11. Kern J, Harris I (1975) On the optimum tilt of solar collector. *Solar Energy* 17:97–102.
12. Mondol JD, Yohanis YG, Norton B (2007) The impact of array inclination and orientation on the performance of a grid-connected photovoltaic system. *Renewable Energy* 32:118–140.
13. Yadav AK, Chandel SS (2013) Tilt angle optimization to maximize incident solar radiation: A review. *Renewable Sustainable Energy Rev* 23:503–513.
14. Swiss Federal Office of Energy (SFOE) (2014) *Gesamte Erzeugung und Abgabe Elektrischer Energie in der Schweiz.*; [*Total Generation and Distribution of Electrical Energy in Switzerland*]. Available at http://www.bfe.admin.ch/themen/00526/00541/00542/00630/index.html?lang=en&dossier_id=00769. Accessed January 2, 2017.
15. Afridi MA, et al. (2017) Determining the effect of soiling and dirt particles at various tilt angles of photovoltaic modules to cite this version. *Int J Eng Works* 4:143–146.
16. Mekhilef S, Saidur R, Kamalisarvestani M (2012) Effect of dust, humidity and air velocity on efficiency of photovoltaic cells. *Renew Sustainable Energy Rev* 16:2920–2925.
17. Dermont C, Ingold K, Kammermann L, Stadelmann-Steffen I (2017) Bringing the policy making perspective in: A political science approach to social acceptance. *Energy Policy* 108:359–368.
18. Wuestenhagen R, Wolsink M, Buerer MJ (2007) Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy* 35:2683–2691.
19. Stoeckli R (2017) The HelioMont surface solar radiation processing 2017 update. Scientific Report MeteoSwiss 93:122.
20. Schmetz J, et al. (2002) An introduction to Meteosat second generation (MSG). *Am Meteorol Soc* 83:977–992.
21. Steinmeier C (2013) CORINE land cover 2000/2006 Switzerland. Final report. Available at http://www.wsl.ch/publikationen/pdf/12359.pdf. Accessed January 1, 2017.
22. Swiss Federal Statistical Office (2014) *Statistik der Bevoelkerung und der Haushalte*; [*Population and Household Statistics*]. Available at https://www.bfs.admin.ch/bfs/en/home/statistics/population.assetdetail.6606496.html. Accessed January 2, 2017.
23. Farr T, Kobrick M (2007) The shuttle radar topography mission. *Rev Geophys* 45:1–133.
24. Swissgrid (2018) *Energy Statistics Switzerland*. Available at https://www.swissgrid.ch/en/home/customers/topics/energy-data-ch.html. Accessed January 2, 2017.
25. MeteoSwiss (2017) *Automatic Monitoring Network* (Federal Office of Meteorology and Climatology MeteoSwiss, Zurich).
26. Swiss Federal Office of Energy (SFOE) (2018) *Statistik der Wasserkraftanlagen der Schweiz*; [*Statistics of Swiss Hydropower Plants*]. Available at http://www.bfe.admin.ch/themen/00490/00491/index.html. Accessed January 2, 2017.
27. Swiss Federal Office of Energy (SFOE) (2018) *Fuellungsgrad der Speicherseen*; [*Filling Level of Reservoirs*]. Available at http://www.bfe.admin.ch/themen/00526/00541/00542/00630/index.html?lang=en&dossier_id=00766. Accessed January 2, 2017.