Correlations Between Large-Scale Solar and Wind Power in a Future Scenario for Sweden

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***Abstract*—Future power systems are likely to include large amounts of variable power generation such as solar and wind power. As a variable output has to be balanced by the power system's reserves, it is important to study the time variability, coincidence, and correlations between power sources. The effect of output smoothing from dispersion of wind power plants is well established, but there is a need to study more renewables in combination. This study analyses large-scale solar and wind power in a future scenario for Sweden, using climatic data covering eight years with an hourly resolution. It is shown that solar and wind power are negatively correlated on all time scales, from hourly to annual, but that the correlation is strongest for monthly totals. Combining solar and wind power reduces total variations in terms of standard deviation, but hour-to-hour variability is always higher with a larger share of solar power.**

***Index Terms*—Correlation, power generation availability, power generation meteorological factors, solar power generation, wind power generation.**

I. Introduction

THE European Parliament states, in its directive on introduction of renewable energy, that 20% of the energy use within the union should be covered by renewable energy sources by 2020 [1]. One important part of this transition is expansion of renewable electricity generation. Judging from current developments, wind power is the power source most likely to reach substantial penetration levels within this time frame. Although wind power currently contributes to approximately 4% of the total electricity generation within the union [2], the penetration level in some areas or countries is much higher [3]. Solar power generation is also increasing worldwide, although it currently provides to only a minor proportion of the total generation mix even at the locations with the highest penetration levels. However, if the current trends for grid-connected photovoltaics (PV) continue, combined with decreasing system costs, a future expansion of solar power generation is not unlikely.

Both solar power and wind power are intermittent power sources. Solar power follows annual and diurnal insolation patterns, caused by the earth's movement around the sun and disturbed by cloud movements, while wind power follows local wind speed variations caused by moving weather fronts.

Such intermittent generation has a number of impacts on the power system, including both generation and transmission. Variable production from hour to hour changes scheduling of other generation units and the use of transmission between geographic areas. Unpredicted generation has to be handled by system reserves; however, as the basis for control often is a large geographical area where fluctuations coincide randomly, every unpredicted increase or decrease in power from individual generation units does not have to be met by a change in a control unit. A more dispersed generation results in a smoother combined output profile, which reduces forecast errors, lets conventional thermal capacity run more evenly and at higher efficiency, and puts less requirements on reserves. For wind power it has been estimated, taking the smoothing effect into account, that a 10% increase in the wind power penetration of gross demand increases the reserve requirements by 2%–8% of rated wind power capacity [4].

The effect of smoothing from dispersion has been well-researched for wind power. After early studies by Kahn [5] on American wind stations and Landberg [6] on European sites, many studies have reached the same conclusions: dispersion leads to decreased variations and increased availability (overviews of previous research can be found, e.g., in [3], [7], and [8]). Regarding the latter observation, Archer and Jacobson [9] showed that as few as eight different sites were sufficient to eliminate the probability for zero wind power output. In a large study for the Nordic countries, Holttinen [10] studied variability and correlations between wind farms. In general, positive correlations between generators enhance variations whereas uncorrelated power outputs coincide randomly to reduce variations. For solar power this smoothing effect has not been as thoroughly investigated, although some studies exist that show considerable smoothing of weather-induced fluctuations [11], [12].

As future power systems may include a number of different large-scale intermittent power sources, such as solar and wind power, it is interesting to study the effect on combined dispersed power outputs from such combinations. Most studies of combined solar and wind power systems have been on small-scale hybrid systems (an overview has been presented by Zhou *et al.* [13]). Combinations of wave and wind power have been analyzed [8], [14] and some studies on higher systems levels that incorporate both wind and solar, have been presented [15], [16], but none that investigate the combined time variability and correlations in detail, as has been done for wind power.

This study aims at describing and analyzing the variability in, and correlations between, large-scale solar and wind power

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in a future scenario for Sweden, as part of a project that is to determine the potential for distributed PV in the country. A fundamental assumption for the project is that wind power will already be integrated in the power system when solar power is introduced on a large scale, which makes it necessary to study them in combination. Currently wind power in Sweden produces around 2 TWh annually, but the national long-term planning goal has recently been upgraded from 10 to 30 TWh per annum [2]. In comparison, solar power still contributes marginally, currently with around 1 GWh per year [17]. These figures should be compared to the annual Swedish electricity demand, which is currently around 140–150 TWh.

Solar and wind power generation amounting to 10 TWh annually are analyzed in this paper, corresponding to installed capacities that could be reached within the next decades. Power output data series for multiple generation units covering eight consecutive years with an hourly resolution, modeled from historical climate data, are utilized. While an existing scenario for wind power is used, a main scenario for solar power based on mounting on available building surfaces is constructed and compared to other concepts for large-scale solar power integration. Correlations between individual units, smoothing in aggregate production and variability in the combined output are analyzed statistically.

Section II describes the data underlying the analyses; Section III summarizes the applied methodology for PV simulation and statistical evaluation and the studied scenarios are presented. Results are presented in Section IV and are discussed in Section V. Some conclusions are finally drawn in Section VI.

II. Data

The correlation analysis is based on hourly series of (A) irradiation and temperature, to which a photovoltaic conversion model is applied, and (B) modeled wind power in an existing scenario. The studied time period covers the eight years 1992–1999 (70 128 hourly values) and was chosen to match the time span of the wind power database while avoiding gaps in the irradiance data series. These data sources are described in more detail below.

A. Solar Irradiation and Temperature

The Swedish Meteorological and Hydrological Institute (SMHI) has measured solar irradiance at 12 locations in Sweden since 1983 [18]. The stations are indicated in Fig. 1 and listed in Table I. In this study hourly global and diffuse radiation data series from all of these stations were used, covering the period 1992–1999. After 1999 there are gaps in some of the radiation data series, which is why this end point was chosen. Ambient air temperature data with varying time resolution for the same period were obtained from locations as close to the radiation stations as possible.

Although the studied time period was chosen to minimize the risk for data loss, there are missing data on some occasions. However, the occurrence is very small and has an insignificant impact on the total database [18]. Missing data were handled differently depending on the application (see Section III).

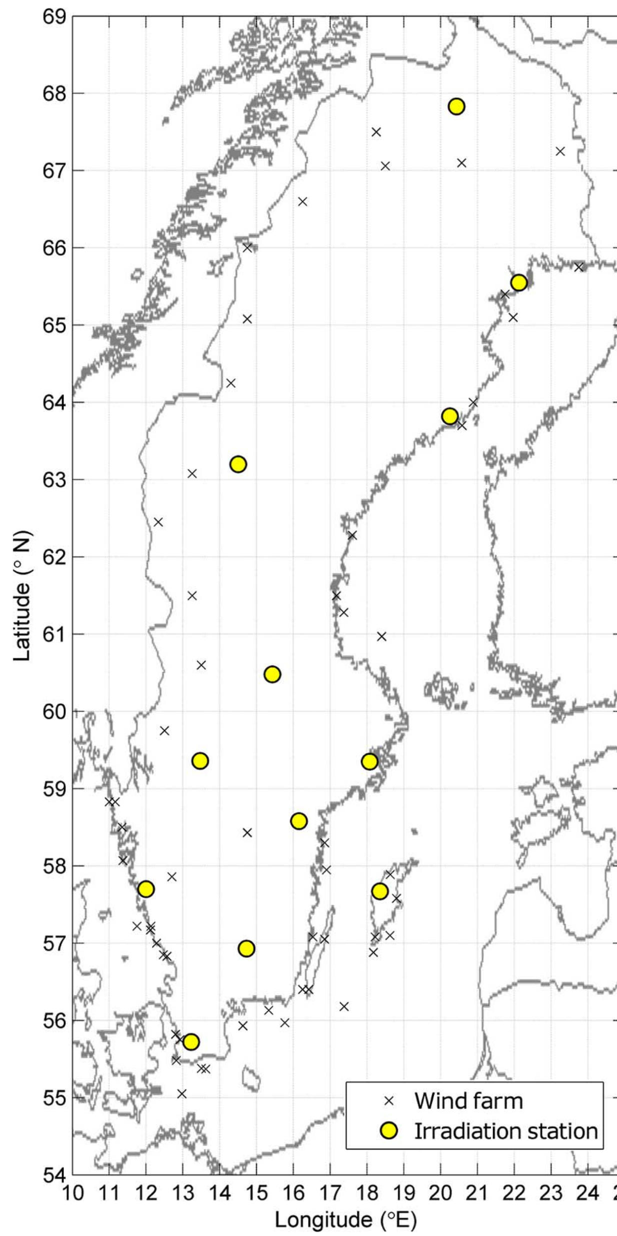

Fig. 1. Locations of wind farms and solar radiation stations in the analyzed data sets.

B. Wind Power

Wind power data series for the eight-year period were obtained from an existing database of modeled wind power in Sweden [19]. This database, in its entirety covering the years 1992–2001, was constructed by SMHI for a scenario of 4000-MW wind power (10 TWh annually) with 56 wind farms of varying capacity located across Sweden. The locations are indicated in Fig. 1. The wind conditions at each site are determined from a mesoscale climatic model [20] that interpolates continuous observations from weather stations, radars, and satellites in an 11×11-km grid. The time resolution is hourly, as for the solar radiation data.

III. Methodology

The solar power scenarios are constructed from measured irradiance and temperature data. This modeling is outlined below (Section III-A), as well as the different scenarios (III-B), and the fundamentals of the statistical correlation analysis (III-C).

A. Photovoltaic System Modeling

For a PV system with specified tilt and azimuth angles, the in-plane global radiation I_T is determined from measured diffuse and beam (global minus diffuse) radiation on the horizontal plane. In-plane beam radiation is calculated with standard transposition formulas [21], in-plane diffuse radiation with the Hay and Davies model [22], and ground-reflected radiation from the standard view factor formula [21] weighted by a mean albedo of 0.2. In this process, the extraterrestrial solar radiation is also calculated, which is the radiation reaching the earth undisturbed by the atmosphere.

The PV system output is determined in every time step k as

$$P(k) = AI_T(k)\eta_c(k)\eta_{\rm add} \quad (1)$$

where A is the surface area of the PV array, η_c is the conversion efficiency, and $\eta_{\rm add}$ represents further array losses and losses in additional equipment such as inverters. The conversion efficiency is dependent on the incident radiation and the measured ambient temperature T_a and is expressed as [21]

$$\eta_c(k) = \eta_{c,\rm STC}\left[1 - \mu\left(T_a(k) - T_{c,\rm STC} + CI_T(k)\right)\right] \quad (2)$$

where $\eta_{c,\rm STC}$ is the reference efficiency at standard test conditions (STCs), μ is the temperature coefficient of the solar cells, $T_{c,\rm STC}$ is the cell temperature at STC, and C is the coefficient for the irradiance dependence, determined with the $NOCT$ method [21]. The model parameters were set to values representative for a system with crystalline silicon solar cells and a standard inverter ($\eta_{\rm add} = 0.8$, $\eta_{c,\rm STC} = 0.14$, $\mu = 0.4\%/°$C, $T_{c,\rm STC} = 25$ °C, and $C = 0.028°\mathrm{Cm}^2 \cdot \mathrm{W}^{-1}$).

When calculating solar power profiles for each station, missing radiation data are handled by replacing values in the power output series with calculated output from an adjacent station. The same procedure applies to large gaps in the temperature data. When temperature data are missing occasionally or when the time resolution is lower than hourly, missing values are replaced by the previously available one. In total, as seen over the whole data set, 0.1% of the values were missing and had to be replaced.

B. Scenarios

To compare the characteristics of solar and wind power, the respective capacity is set to produce the same amount of electricity annually. The main studied scenario is based on 10-TWh mean annual production of solar and wind power separately over the eight-year period (approximately 7% of the total annual Swedish electricity supply). This is the wind power production in the previously developed wind power scenario, which is used in its existing form.

TABLE I
Radiation Stations and the Associated Maximum Available Building Areas for PV Mounting in Sweden

Radiation station	Location		Tilted area (% of total)					Total area
	Lat (°N)	Long (°E)	0°	19°	28°	45°	90°	(km^2)
Lund	55.72	13.22	5	12	27	12	44	102
Växjö	56.93	14.73	4	10	24	21	41	52
Visby	57.67	18.35	3	8	22	27	39	7
Göteborg	57.70	12.00	5	13	25	15	43	151
Norrköping	58.58	16.15	4	11	26	15	43	72
Stockholm	59.35	18.07	5	15	27	6	47	120
Karlstad	59.37	13.47	4	9	23	24	40	31
Borlänge	60.48	15.43	4	11	25	17	42	79
Frösön	63.20	14.50	4	10	19	29	39	18
Umeå	63.82	20.25	4	10	23	22	41	53
Luleå	65.55	22.13	4	12	25	17	42	24
Kiruna	67.83	20.43	–	–	–	–	–	–
Total			4	12	25	15	43	709

Note: The Kiruna station was not used in the scenarios. Both Luleå or Kiruna are located in the same county but the former was chosen, as it is more representative of the location of the built environment. Orientations of tilted surfaces was uniformly distributed between −90° and 90°.

In some calculations, a combined solar and wind power profile is studied. In these cases, the *total* production is set to 10 TWh, which means that either solar or wind is scaled down. This procedure assumes that the production is located at the same sites with the same relative distribution of capacity and that the production at each location is scaled.

The main scenario for solar power assumes that building-mounted PV is integrated with a uniform degree of expansion over the built environment in Sweden. The scenario distributes per-county available building areas on the radiation stations (except for the northernmost Kiruna station), based on previous studies of solar energy availability on building surfaces in Sweden [23] combined with statistics on the geographical distribution of different building types obtained from residential statistics and real estate tax assessments. The distribution of differently tilted maximum available areas on the radiation stations is summarized in Table I. The combined PV profile is obtained by simulating an output profile (1) for each such individual building area and adding them together.

Two alternative PV scenarios were constructed for comparison: one with optimally oriented systems and one with two-axis tracking systems. In both scenarios, equally sized systems located at the same radiation stations as in the building-mounting scenario are assumed. Fig. 2 shows how utilization of the available solar energy can be improved by optimizing the system orientation, with two-axis tracking systems collecting 50%–60% more of the incoming radiation than the horizontal plane. Except for the northernmost station (Kiruna), there is no clear trend towards lower annual insolation levels on tilted or tracking planes for higher latitudes, which does not make it more likely with, for example, a higher degree of expansion of PV in southern Sweden.

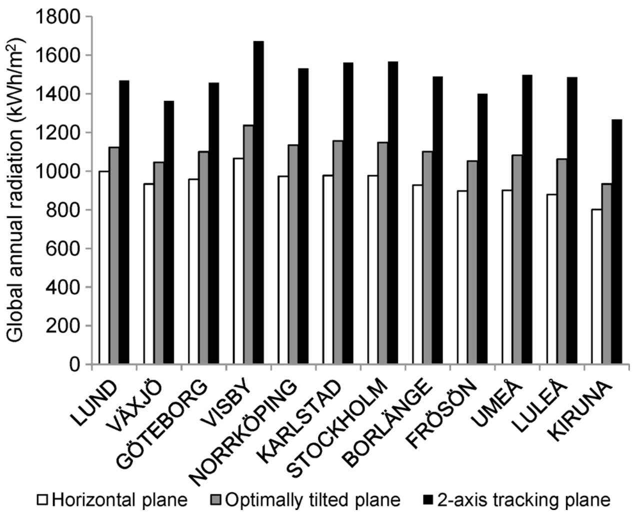

Fig. 2. Incident solar radiation on differently oriented surfaces.

C. Statistical Analysis

The main statistical measure in this study is the *sample correlation coefficient*, applied to two data series $X(k)$ and $Y(k)$

$$\rho_{X,Y} = \frac{\sum_k \left(X(k)-\bar{X}\right)\left(Y(k)-\bar{Y}\right)}{\sqrt{\sum_k \left(X(k)-\bar{X}\right)^2}\sqrt{\sum_k \left(Y(k)-\bar{Y}\right)^2}}. \quad (3)$$

The correlation coefficient is 1 when the data series are perfectly positively correlated and -1 when there is a perfect negative correlation. A zero value corresponds to a complete lack of correlation. The coefficient is used to determine both the interdependence between radiation stations and wind farms and between solar and wind power generation profiles. When analyzing the correlation between original radiation data series, indices with missing values are simply omitted from the calculations.

For combinations of solar and wind power, a more detailed analysis is done on the variations of a combined production profile $P(k)$, as well as on the *power ramp* function

$$\Delta P(k) = P(k) - P(k-1) \quad (4)$$

which describes how the output changes from hour to hour and is critical for the power system on the hourly operational time scale.

IV. Results

A. General Production Characteristics

Some general characteristics of the solar and wind power scenarios are shown in Table II. It can be seen that to produce the same amount of electricity annually, the rated (STC) solar peak power has to be at minimum twice as high as the wind power capacity. The differences in rated peak power and solar cell area reflect the differences in collection of solar radiation between the system orientations. Building-mounted systems require the largest area, corresponding to 14% of the maximum available areas (cf. Table I). The actual peak power, which is the maximum produced power, differs less. It is worth noting

TABLE II
Production Statistics for the Solar and Wind Power Scenarios

Power source	Rated peak power (GW)	Actual peak power (GW)	Total area (km^2)
Solar power, optimally tilted	11,2	9,2	80
Solar power, 2-axis tracking	8,4	7,2	60
Solar power, building-mounted	13,9	8,0	99
Wind power	4,1	3,9	–

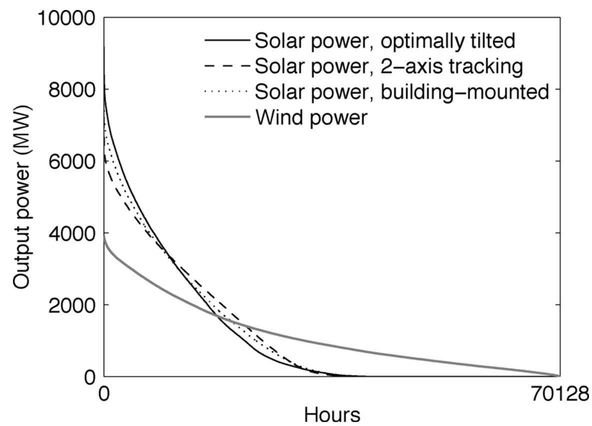

Fig. 3. Duration curves for the main solar power scenario (building-mounted), the two additional solar power scenarios, and the wind power scenario. The total production in every case is 10 TWh per year.

that the actual peak power is highest for the optimally tilted systems, due to the similarity in solar radiation collection. The tracking systems collect radiation more evenly over the day and the building-mounted systems have a lower combined peak as they do not receive their maximum insolation at the same time.

The duration graphs in Fig. 3 show that the distribution of the output power is not very different between the three solar power scenarios, but that they all differ considerably from the wind power distribution, since the solar power is completely unavailable during half of the total time (nights). Because of the slight differences, only the main scenario with building-mounted PV is considered in the following.

B. Correlations Between Stations

Fig. 4 shows the hourly correlations between individual solar radiation stations and wind farms (a) and between radiation stations and wind farms (b) and the dependence of the correlations on the distance between the locations. The figure shows that the correlation is strong between adjacent wind farms, but decreases with distance. For distances longer than 500 km, the correlation is between 0.2 and 0.4 and for the longest distances around 0.1. This is in accordance with previous results for wind power and is due to the fact that weather fronts do not affect the whole country at the same time.

Contrary to the wind power data, the correlation between radiation stations is consistently stronger and converges to somewhere just below 0.8 for the longest distances. This is because all stations follow very similar seasonal and diurnal insolation

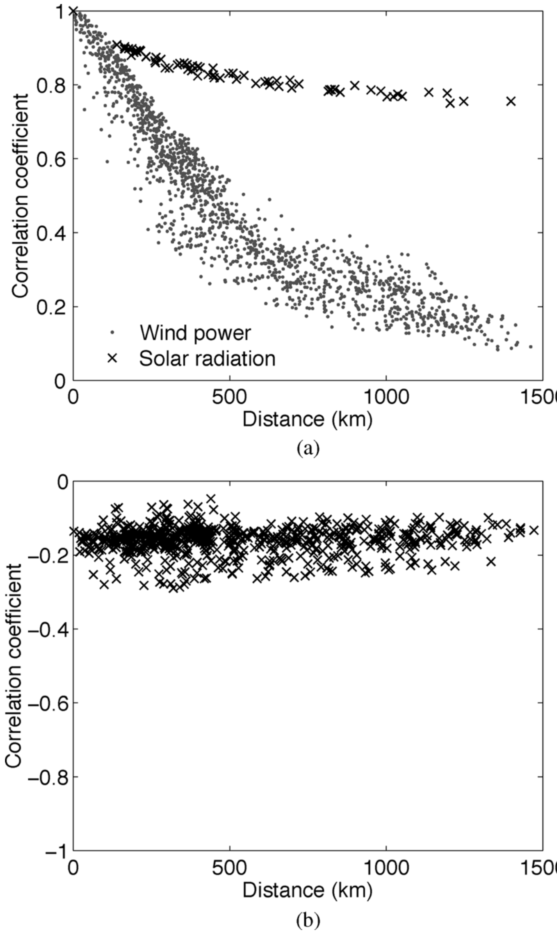

Fig. 4. Correlations between individual wind farms and solar radiation stations. (a) Correlations between each pair of the 12 radiation stations and each pair of the 56 wind farms, respectively. (b) Correlations for combinations of wind farms and radiation stations.

patterns. Although there are differences between the high-latitude and low-latitude locations, the fluctuations of the incident extraterrestrial radiation undisturbed by atmospheric phenomena are highly similar. For the studied locations, the correlation coefficient for extraterrestrial radiation on the horizontal plane was at minimum 0.98. The local weather conditions then cause the decrease from 1 to 0.8. The correlations between individual solar radiation stations and wind farms are slightly negative with a very weak trend towards lower correlation for longer distances.

Taken together, these results suggest that there will be a smoothing effect on the aggregate output of distributed solar power, but weaker than that for wind power. A smoothing effect for combinations of solar and wind power is also suggested because of the slightly negative correlation, but the lack of a clear relation to distance shows that this will not be dependent on the relative locations of solar and wind power sites.

Examples of the smoothing effect for wind and solar power, respectively, is shown in Fig. 5. The duration graphs show that the output power is more evenly distributed for all generation units combined, but that the smoothing effect is more pronounced for wind power.

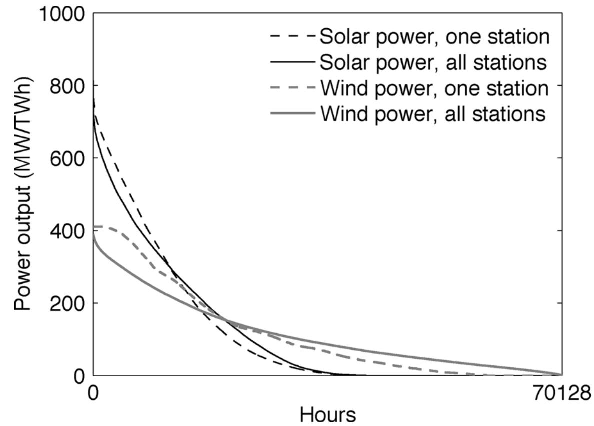

Fig. 5. Examples of the smoothing effect from dispersion for solar power and wind power, respectively. The power output in MW is normalized by the annual production in TWh.

C. Correlations Between National-Scale Solar and Wind Power

The correlations between total national building-mounted solar power and wind power, on different time scales, are shown in Fig. 6. In (a) a negative correlation is seen between annual totals of solar and wind power. This suggests that more windy years are less sunny, and *vice versa*. However, a longer sequence of years would be needed to determine if this pattern is consistent.

According to Fig. 6(b)–(d), the correlation increases with the integration time and is strongest for monthly totals, where there is a very clear negative correlation. On the hourly time scale the correlation is weak, and it is also seen in the average daily profile that there is no evident diurnal fluctuation in wind power over the year on the national scale, whereas for solar power the diurnal pattern is very clear.

These negative correlations suggest that a combination of solar and wind power would even out fluctuations, but it is not clear on which time scales. As there are fluctuations both on seasonal and diurnal time scales, the seasonal correlations could still be visible in the correlation coefficients for hourly and daily series. To separate these time scales, correlation coefficients were evaluated for hourly and daily totals within each month. The results are shown in Table III. Now the correlation in hourly values is near zero and although the daily correlations are not particularly strong, they suggest that to some extent less solar power is produced during windy days while the wind power production is lower during sunny days.

D. Combinations of Solar and Wind Power

The results from the correlation analysis suggest that there is a smoothing effect from combining solar and wind power on a national scale. Fig. 7 shows that this is true for the distribution of combined output levels during the whole studied eight-year period. In all three cases, 10 TWh are produced annually, and the most evenly distributed profile was found for a combination of 3-TWh solar and 7-TWh wind power.

However, this result does not tell if the short time-scale fluctuations are lower with this combination. To determine this the hourly values must be studied in more detail. Table IV shows

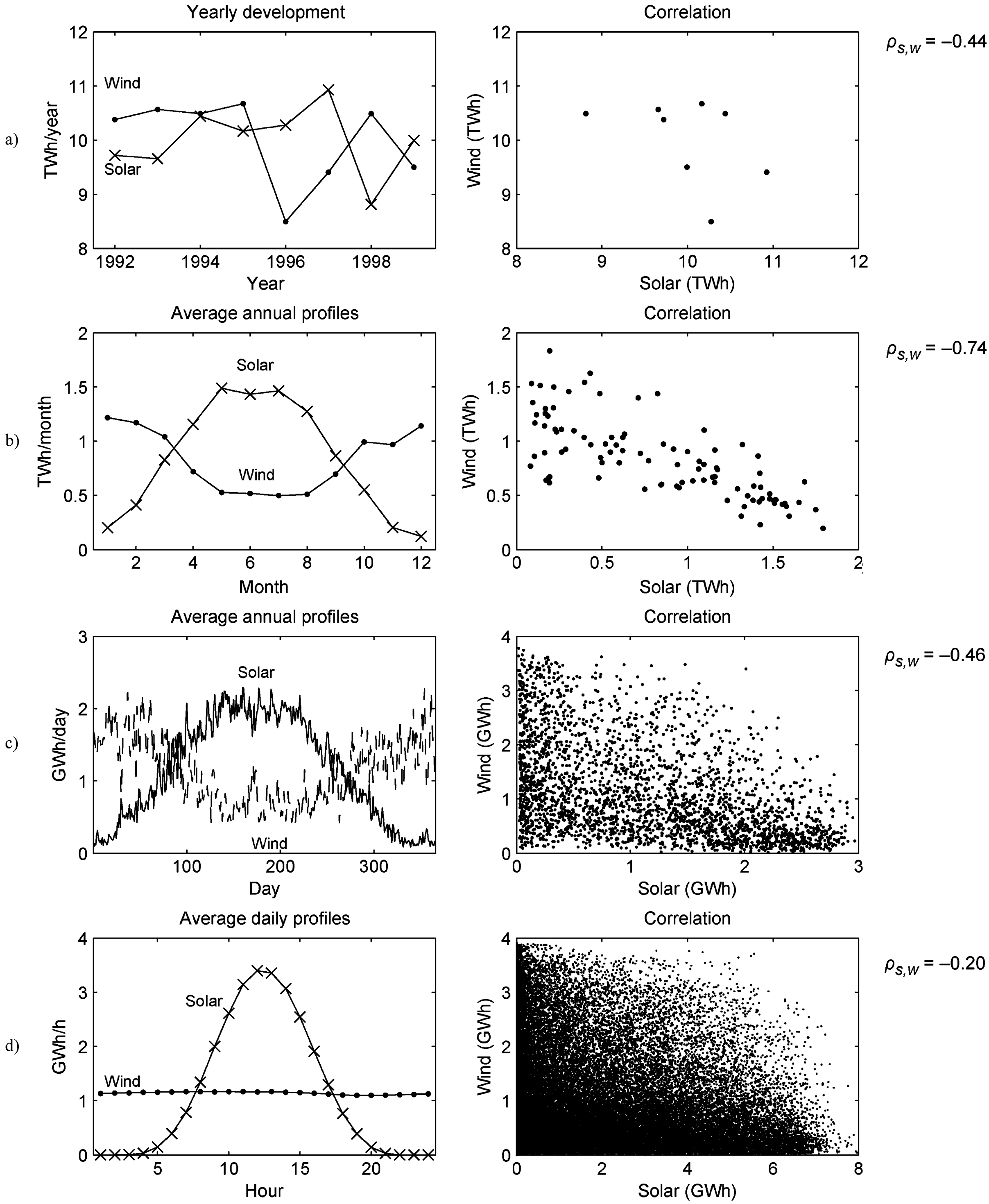

Fig. 6. Variability and correlations between national-scale solar and wind power on different time scales. (a) Annual totals; (b) monthly totals; (c) daily totals; (d) hourly totals.

the variations in the total output P and the ramp function ΔP for combinations of solar and wind power. As suggested by Fig. 7, the standard deviation of P has a minimum at 3-TWh solar and 7-TWh wind power, but the hour-to-hour fluctuations are consistently higher with a larger share of solar power. For example, the average change from hour to hour is six times higher and the maximum change four times higher with 100% solar power compared to 100% wind power. The standard deviation of P and ΔP are also shown in Fig. 8, where the minimum in the standard deviation of P is clearly seen.

The evened-out distribution of output power over the year is mainly a seasonal effect: wind power production is higher during winter while solar power production is higher in the summer. Combining the two sources means winter capacity can be decreased while summer capacity can be increased. This is why the combination of 3-to-7 provides the minimum:

TABLE III
CORRELATION BETWEEN HOURLY AND DAILY TOTALS OF NATIONAL-SCALE SOLAR AND WIND POWER GENERATION IN EACH MONTH

Month	Correlation coefficient	
	Hourly totals	Daily totals
January	–0,10	–0,25
February	–0,11	–0,30
March	–0,07	–0,26
April	–0,09	–0,32
May	–0,08	–0,42
June	–0,04	–0,35
July	–0,06	–0,48
September	–0,07	–0,41
October	–0,07	–0,20
November	–0,06	–0,16
December	–0,02	–0,03

TABLE IV
FLUCTUATIONS IN COMBINED NATIONAL-SCALE SOLAR AND WIND POWER GENERATION

Annual production (TWh)		Combined output, P			Hourly change, $\|\Delta P\|$		
Solar	Wind	Mean (GW)	Max (GW)	Std. dev. (GW)	Mean (GW)	Max (GW)	Std. dev. (GW)
10	0	1,14	7,97	1,72	0,31	3,23	0,42
9	1	1,14	7,18	1,54	0,28	2,90	0,37
8	2	1,14	6,46	1,35	0,25	2,57	0,33
7	3	1,14	5,81	1,18	0,22	2,25	0,29
6	4	1,14	5,23	1,03	0,19	1,92	0,25
5	5	1,14	4,75	0,89	0,17	1,59	0,20
4	6	1,14	4,45	0,80	0,14	1,30	0,16
3	7	1,14	4,26	0,75	0,11	1,00	0,12
2	8	1,14	4,08	0,76	0,09	0,71	0,08
1	9	1,14	3,89	0,82	0,06	0,71	0,06
0	10	1,14	3,91	0,93	0,05	0,79	0,05

the actual peak powers are then approximately the same (cf. Table II).

However, solar and wind power fluctuate on different time scales. Regardless of the weather conditions, solar irradiation increases from zero to a higher level in a few hours in the morning and conversely in the night, while wind power normally fluctuates on longer time scales. Therefore, despite the negative correlations as seen over the whole year, hourly changes in solar power production are not met by as sudden changes in wind power in the other direction and, thus, a higher fraction of solar power will always lead to larger hourly fluctuations.

V. DISCUSSION

The main results from the study are that it is possible to get a more evenly distributed output with combined solar and wind power generation than with any of the sources alone, due to the negative seasonal correlations, but that the variability on the

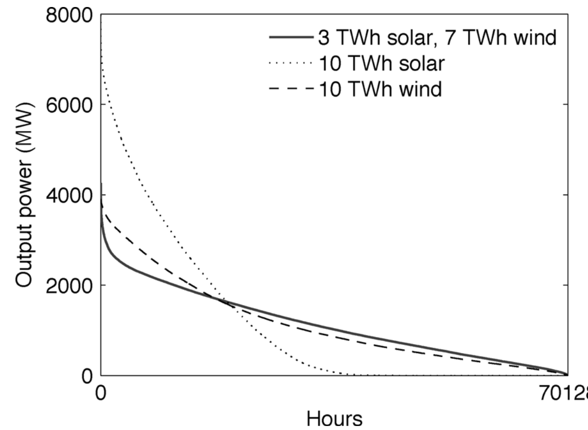

Fig. 7. Duration curves for 10-TWh solar and wind power and the combination of solar and wind power that flattens the production profile maximally.

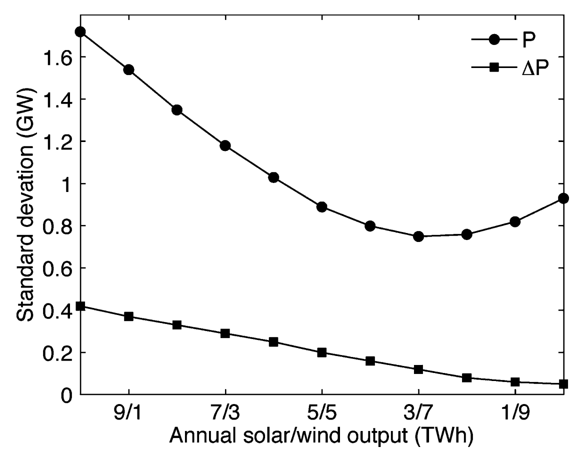

Fig. 8. Standard deviation of the combined solar and wind power output (P) and the absolute value of the ramp function ($|\Delta P|$).

hourly time scale is lowest with wind power. This result is obtained for Swedish data but should be generally applicable, at least for similar climates.

Some improvements or extensions of the applied method could be done. Solar power has been modeled from 11 stations. The smoothing effect could be higher with more stations, although this would not have any decisive impact on the results obtained here. It could also be interesting to go into more detail on whether certain local climatic conditions affect correlations between solar and wind power.

Two important aspects are not covered in this study but should be investigated to determine the effects of a combination of solar and wind power on the power system: predictability of solar power as compared to wind power and the ability of the two power sources to match demand requirements. In future work, the data analyzed in this study will be used in an optimization study to determine the effect of a combination of renewable power sources on the Swedish power and district heating systems.

VI. CONCLUSION

In this study, large-scale solar and wind power in Sweden have been modeled, the correlations between the two power sources have been studied and the effects of geographic dispersion and of combining solar and wind power have been determined. The main conclusions are:

1) There is a smoothing effect on the aggregate output resulting from dispersion of generation units for solar power, but lower than that for wind power because of systematic variability in the availability of solar irradiance.
2) Correlations between individual wind farms and solar radiation stations are slightly negative but not dependent on distance.
3) On a national scale, there are negative correlations between solar and wind power on all time scales, from hourly to annual totals, but they are strongest for monthly totals because of systematic and opposite variations in seasonal availability.
4) A combination of solar and wind power generation assumes a minimum standard deviation at 30% solar and 70% wind power (annual production) because of the complementarity indicated by the negative correlations. However, the hour-to-hour variability is always higher with a larger share of solar power because of the faster fluctuations in solar power.

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References

[1] European Parliament, Directive 2009/28/EC Apr. 23, 2009.
[2] IEA Wind, IEA Wind Energy Annual Report 2008 Jul. 2009 [Online]. Available: http://www.ieawind.org/AnnualReports_PDF/2008.html
[3] IEA Wind Task 25, Design and operation of power systems with large amounts of wind power, Finland, VTT Research Notes 2493, VTT [Online]. Available: http://www.ieawind.org/AnnexXXV.html
[4] H. Holttinen and R. Hirvonen, "Power system requirements for wind power," in *Wind Power in Power Systems*, T. Ackermann, Ed. Chichester: Wiley, 2005, pp. 144–167.
[5] E. Kahn, "The reliability of distributed wind generators," *Elect. Power Syst. Res.*, vol. 2, pp. 1–14, Mar. 1979.
[6] L. Landberg, "The availability and variability of the European wind resource," *Int. J. Solar Energy*, vol. 18, pp. 313–320, Jan. 1997.
[7] G. Giebel, "Wind power has a capacity credit: A catalogue of 50+ supporting studies," *e-WINDENG J.* Oct. 2005 [Online]. Available: http://ejournal.windeng.net
[8] E. D. Stoutenburg, N. Jenkins, and M. Z. Jacobson, "Power output of co-located offshore wind turbines and wave energy converters in California," *Renew. Energ.*, vol. 35, pp. 2781–2791, Dec. 2010.
[9] C. L. Archer and M. Z. Jacobson, "Spatial and temporal distributions of U.S. winds and wind power at 80 m derived from measurements," *J. Geophys. Res.*, vol. 108, no. D9, p. 4289, May 2003.
[10] H. Holttinen, "Hourly wind power variations in the Nordic countries," *Wind Energy*, vol. 8, pp. 173–195, Apr./Jun. 2005.
[11] E. Wiemken, H. G. Beyer, W. Heydenreich, and K. Kiefer, "Power characteristics of PV ensembles: Experiences from the combined power production of 100 grid connected systems distributed over the area of Germany," *Sol. Energy*, vol. 70, pp. 513–518, 2001.
[12] K. Otani, J. Minowa, and K. Kurokawa, "Study on areal solar irradiance for analyzing areally-totalized PV systems," *Sol. Energ. Mat. Sol. C.*, vol. 47, pp. 281–288, Oct. 1997.
[13] W. Zhou, C. Lou, Z. Li, and H. Yang, "Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems," *Appl. Energ.*, vol. 87, pp. 380–389, Feb. 2010.
[14] F. Fusco, G. Nolan, and J. V. Ringwood, "Variability reduction through optimal combination of wind/wave resources—An Irish case study," *Energy*, vol. 35, pp. 314–325, Jan. 2010.
[15] H. Lund, "Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply," *Renew. Energ.*, vol. 31, pp. 503–515, Apr. 2006.
[16] D. Heide, L. von Bremen, M. Greiner, C. Hoffmann, M. Speckmann, and S. Bofinger, "Seasonal optimal mix of wind and solar power in a future, highly renewable Europe," *Renew. Energ.*, vol. 35, pp. 2483–2489, Nov. 2010.
[17] Elforsk, Grid-Connected PV Systems in Sweden [Online]. Available: http://www.elforsk.se/solenergi/ViewPlantsInSweden.aspx
[18] T. Persson, Measurements of solar radiation in Sweden 1983–1998 SMHI, Sweden, Reports Meteorology and Climatology N:o 89, 2000.
[19] M. Magnusson, R. Krieg, M. Nord, and H. Bergström, Effektvariationer av vindkraft—En studie av vindenergiproduktionens tidsvariation (Variations in Wind Power—A Study of the Time Variability of Wind Energy) Elforsk Report 04:34, Dec. 2004.
[20] SMHI, Mesan—An Operational Mesoscale Analysis System [Online]. Available: http://www.smhi.se/sgn0106/if/meteorologi/mesan.htm
[21] J. A. Duffie and W. A. Beckman*, Solar Engineering of Thermal Processes*, 2nd ed. New York: Wiley Interscience, 1991.
[22] J. A. Davies and J. E. Hay, "Calculation of the solar radiation incident on an inclined surface," in *Proc. First Canadian Solar Radiation Data Workshop*, pp. 59–72.
[23] E. Kjellsson, Potentialstudie för byggnadsintegrerade solceller i Sverige—Rapport 1: Ytor på byggnader (Potential Study for Building-Integrated Photovoltaics in Sweden—Report 1: Building Areas) Lund University, Sweden, Report TVBH-7216, 2000.

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