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# Meteorological Wind Energy Potential of the Alps Using ERA40 and Wind Measurements of the Tyrolean Alps

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## Abstract:

Wind measurement sites in the Tyrolean Alps were evaluated concerning their wind energy potential. We used global reanalysis ERA40 data and data from wind measurement stations and analysed them statistically.

Due to the decrease of density with height, alpine sites suffer from a nearly linear decrease of harvestable power with altitude, which is more than offset by the increase of wind speed at altitudes above 1.5 km MSL. ERA40 data showed higher potential on the northern than on the southern side of the Alps. Best locations are not isolated peaks but on ridges within wide orographic channels through which the frequently different air masses on both sides of the Alps equilibrate. The best potential sites have median wind speeds of up to 7.1 m/s and extractable potentials between 2900 and 1600 kWh per year and square meter of rotor area. The profile of horizontal wind speed at ridge sites is often not logarithmic but approximately constant within the height of a wind turbine due to an often (nearly) complete absence of upwind fetch. Icing can cause considerable downtimes.

**Keywords:** wind energy, complex terrain, Alps, icing, quality control, gap flows, wind measurement sites

## 1 Introduction

As wind energy usage increases, wind turbines are moving into more challenging locations. Much of the knowledge about wind power meteorology cannot simply be transferred to the alpine setting. Therefore, within the scope of the EU-Interreg IIIb

project Alpine Windharvest (2001 to 2006) we evaluated wind measurement sites in the Tyrolean Alps from a meteorological point of view.

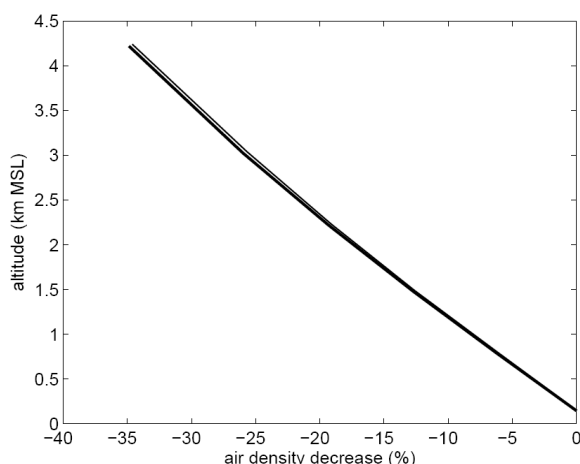
## 2 Meteorological data and their processing

Four data sources were used: firstly, 45 years of data from the global reanalysis ERA40 from ECMWF [1] to elucidate large scale differences between the Alps and similar altitudes above the lowlands and between the northern and southern side of the Alps. The second data source constitutes several years of measurements from routine networks in the Tyrolean Alps to identify topographic features that boost wind energy yield. The third data are spatially dense but only short-term (70 days) measurements in the vicinity of the meteorologically most promising wind energy site in the Tyrolean Alps. They were used to study the influence of small-scale topographical variations, of valleys, and of using short measurement periods for evaluating wind energy potential. The fourth data source was Doppler sodar measurements at the most promising site to highlight differences between vertical profiles of horizontal wind over flat terrain and mountain ridges/gaps. All the data were analysed statistically.

The wind measurements came from automatic weather stations, which are often located in exposed mountainous locations. Quality control was performed to ensure that the 10-minute average data were in physical range and that periods with ice-covered anemometers were eliminated.

## 2.1 Wind situation and meteorological aspects in the Alps

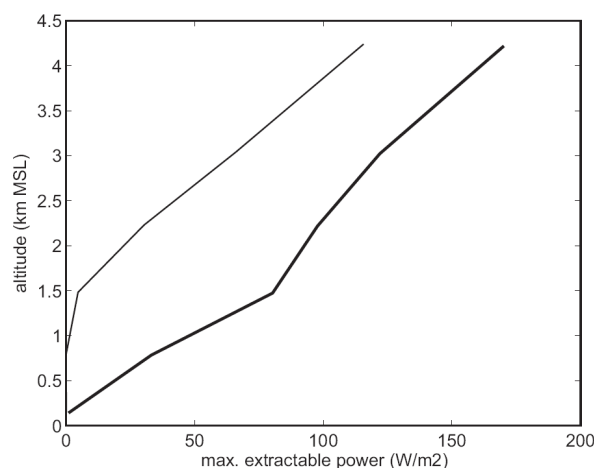
Alpine wind energy sites lie in about 1500 m and 3500 m MSL. This leads to an approximately 15-30% decrease of available wind power because of the decrease of air density with height (Fig. 1). However, higher speeds that occur at higher altitudes due to the poleward temperature decrease lead to a resulting increase of extractable power above 1.5 km MSL. Since the strongest horizontal gradient of temperature lies to the north of the Alps most of the time, wind speeds there are considerably higher. Consequently, extractable power above the northern rim of the Alps is much higher than above the southern rim. (Fig. 2)



**Figure 1: Decrease of air density relative to the 1000 hPa level (approx. 150 m MSL) with altitude. The density decrease is directly proportional to a decrease of wind power. Vertical profiles of density are from ERA40 averaged over 45 years for grid points north (thin line, 48.375N, 10.125N, close to Ulm Germany) and south (bold: 45N, 10.125E, close to Parma, Italy) of the Alps, respectively.**

The Alps are not a homogeneous ridge but have many indentations *through* which the air can flow. These indentations can form more or less regular and wide channels. In general, air flowing through a narrowing of the terrain, a gap, accelerates so that wind speeds may become substantially higher than the oncoming wind speeds upstream of the Alps [2].

Since the Alps lie approximately perpendicular to the average north-south temperature gradient they frequently separate air masses of different temperatures on the northern and southern rims. This temperature difference causes a pressure difference, which in turn accelerates the air. Since often the temperature difference between the two sides of the Alps is confined to below the alpine crest, the air masses can only accelerate and equilibrate through the gaps in the alpine crest. Frequent strong winds should therefore occur in these gaps [2]. Above these gaps, wind speeds on isolated mountain peaks are reminiscent of the free atmosphere above the lowlands.



**Figure 2: Vertical profile of average extractable power calculated from wind speeds over 45 years from the ECMWF reanalyses at two locations along the northern rim of the Alps (bold: 48.375 N, 10.125 E, close to Ulm) and one location along the southern rim of the Alps (thin: 45 N, 10.125 E, close to Parma). Locations marked with circles in Fig. 5**

Since the strong westerlies and the polar front zone move northwards in summer, winds in the colder seasons can reach values of about twice the strength of winds in summer.

## 2.2 Computation of wind energy potential parameters

Frequently wind energy potential is stated using the total wind power (i.e. the advection of the kinetic energy). However, as Betz (1922-1925) showed the maximum amount is about 40% lower.

$$P = CB \cdot 0.5 \cdot \rho \cdot A \cdot v^3 \quad (\text{Equ. 1})$$

**Equation 1:  $v$  is the wind speed upstream of the turbine,  $A$  is the cross-sectional area of the turbine's propeller, and  $\rho$  is the density of air.**

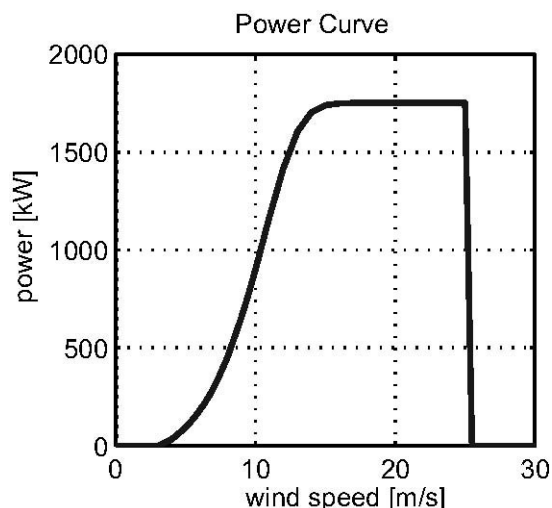
We therefore consider it appropriate to only show the maximum extractable power, i.e. the upper limit. Additionally we give numbers for an exemplary turbine (Fig. 3) as could be installed in mountainous environments. As turbine design keeps improving, this will give a lower limit to the yield that can be expected in the future.

The power computation requires measurements of wind speed and density. Density  $\rho$  itself is not measured directly but computed from temperature  $T$  [K] and pressure measurements  $p$  [Pa] via the equation of state:

$$\rho = \frac{p}{R \cdot T} \quad (\text{Equ. 2})$$

where  $R$  is the specific gas constant for dry air (1004 J (kg K)<sup>-1</sup>). For the stations that did not

measure pressure it was calculated from neighbouring stations.



**Figure 3: Power curve of an exemplary wind turbine used to compute the wind energy that could have been harvested if the turbine had been situated on a wind energy site during the given wind conditions.**

### 3 Results

#### 3.1 Potential at long-term stations in the Tyrol

58 stations were evaluated in the Tyrol region. Out of these, 21 had a median wind speed of below  $2 \text{ m s}^{-1}$ , which is too low to be viable for wind energy use. These are either stations in valleys or shielded by the surrounding topography. Valley floors in that part of the Alps are at the most a few kilometers wide and the valleys are often cut deeply into the surrounding topography. Of the remaining stations, results for the four with the highest extractable power and the best valley location, respectively, are shown in Figure 6 in the Appendix. Common to the four highest-potential stations is that they all are in an orographic channel and/or a gap.

An indication of the difficulty of measuring winds at exposed locations is the data availability between only 41% and 99%. Reasons for low availability are manifold, e.g. icing, sensor failure, logger failure, prolonged interruption of wireless (usually GSM networks) data transmission.

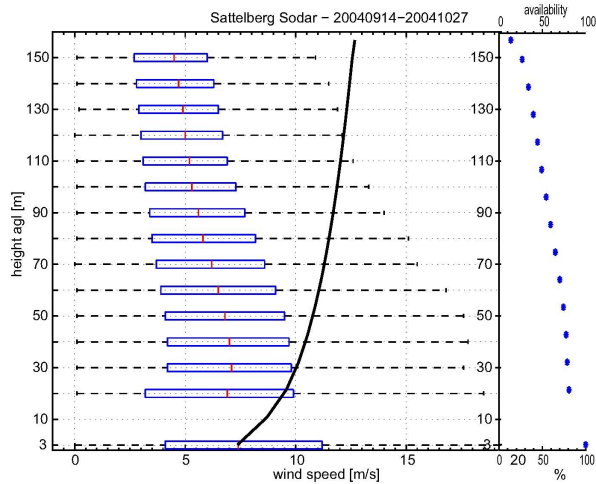
#### 3.2 Effects of local topography and short-term measurements

The Wipp Valley (black rectangle in Fig. 5) is well known for gap flows and related foehn events and thus promises to include potential wind energy sites. Since the valley was densely instrumented during a 70day period, small-scale topographical effects on wind power potential could be examined.

Since the Wipp Valley lies downstream of a narrow pass (Brenner Pass) that runs perpendicular to the main alpine crest, downslope windstorms (Foehn) exist along both valley directions north and south [2]. The valley consists of two gaps: the narrow Brenner corrugation and an upper wide gap at approximately 2100 m MSL with a width of roughly 20 km. The main alpine crest continues on both sides of the pass with an average elevation of 3000 m MSL. The cross-sectional area of the lower Brenner gap is 1/15 of the upper one. Most of the air reaching the downstream (northern) side of the Brenner will therefore have to come through the upper gap. The topography of the valley has influence on its wind power potential. The highest potential can be found in the upper gap where the stations benefit from the gap flow, which attempts to equilibrate between the frequently different air masses on both sides of the Alps. However, stations situated at the narrow bottom of the valley as well as stations above the alpine crest do not show high wind energy potentials. At the valley floor, additional turbulent friction from the side walls lowers the wind speeds. Summits situated above the alpine crest experience winds from the free atmosphere, though, but lack accelerating gap flow.

#### 3.3 Vertical wind profile at a ridge location

The lack of upwind fetch for sites on ridges and peaks invalidates the assumption of a logarithmic like wind profile as over homogenous terrain. Doppler sodar measurements at Sattelberg in combination with a weather station showed that highest wind speeds were in the lowest 3-50 m. Above that to the maximum range of 150 m speeds decreased. The site lacks an upwind fetch in its main wind directions. Further Doppler sodar measurements within the EU project *Alpine Windharvest* in locations outside of the Tyrol confirmed that wind speeds in the height range relevant for wind turbines do not increase with height when there is no fetch from that direction.



**Figure 4: Vertical profile of horizontal wind speed at Sattelberg (SB in Fig. 5) from Doppler sodar measurements and automatic weather station (3 m AGL) 14 September - 27 October 2004. Overlaid is a logarithmic wind profile computed from power-law [4] with exponent of 1/7 starting from the median value of wind speed at 3 m AGL. Data availability (right) decreases with height.**

## 4 Discussion

### 4.1 Comparing these results to sites already used for wind energy

The best potential sites from the semi-operational network have median wind speeds of up to 9.4 m/s and extractable potentials between 2900 and 1600 kWh/(am<sup>2</sup>). This translates to between 2200 and 3500 full load hours.

An already installed alpine wind park in the eastern Alps, the Tauerwindpark, produces less. Eleven turbines harvest a combined 45.5 GWh/a (<http://www.tauernwind.com>), i.e. approximately 4.1 GWh/a, which can be normalized with the area swept by the turbine blades to 1198.4 kWh (am)<sup>-1</sup>.

One wind turbine in Petronell-Carnuntum in Lower Austria produced 1223 kWh/(am)<sup>-1</sup>. This is the highest value ever achieved by a single wind turbine in Austria. The computed corresponding value of the Sattelberg is more than twice as high.

### 4.2 Icing

A detrimental effect of the high altitude of possible alpine wind parks are low temperatures and an accompanying icing problem. The investigations showed that some stations had gaps in the measurement data caused by icing which reached up to almost 50% at some locations. Icing of turbine blades and icing of anemometers need not be concomitant, even though they are closely related. To maximize the

yield of alpine wind parks, special technical solutions to prevent icing might be necessary.

## 5 Conclusion

The wind energy potential evaluated from routine weather station locations in the Tyrol showed that the best locations would outperform flatland sites in eastern Austria and even offshore locations. The area, on which turbines could be erected, is much more limited. Depending on region and altitude, icing could reduce annual yield and call for special technical counter-measures. The highest yields were not found at isolated peaks (which would have extremely limited or no space for turbines anyways) but in ridges and peaks in wide orographic channels, i.e. not on the valley floor along the deepest incisions.

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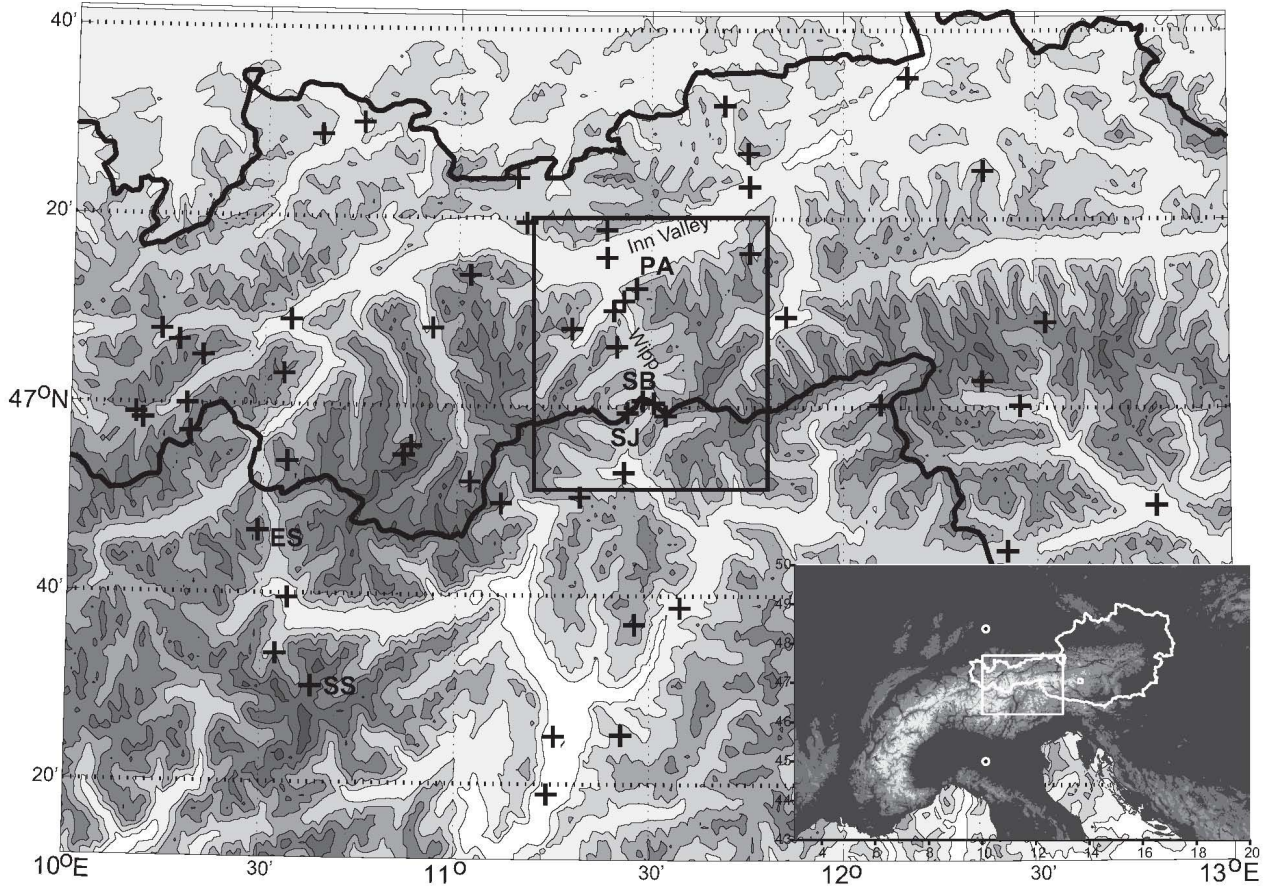
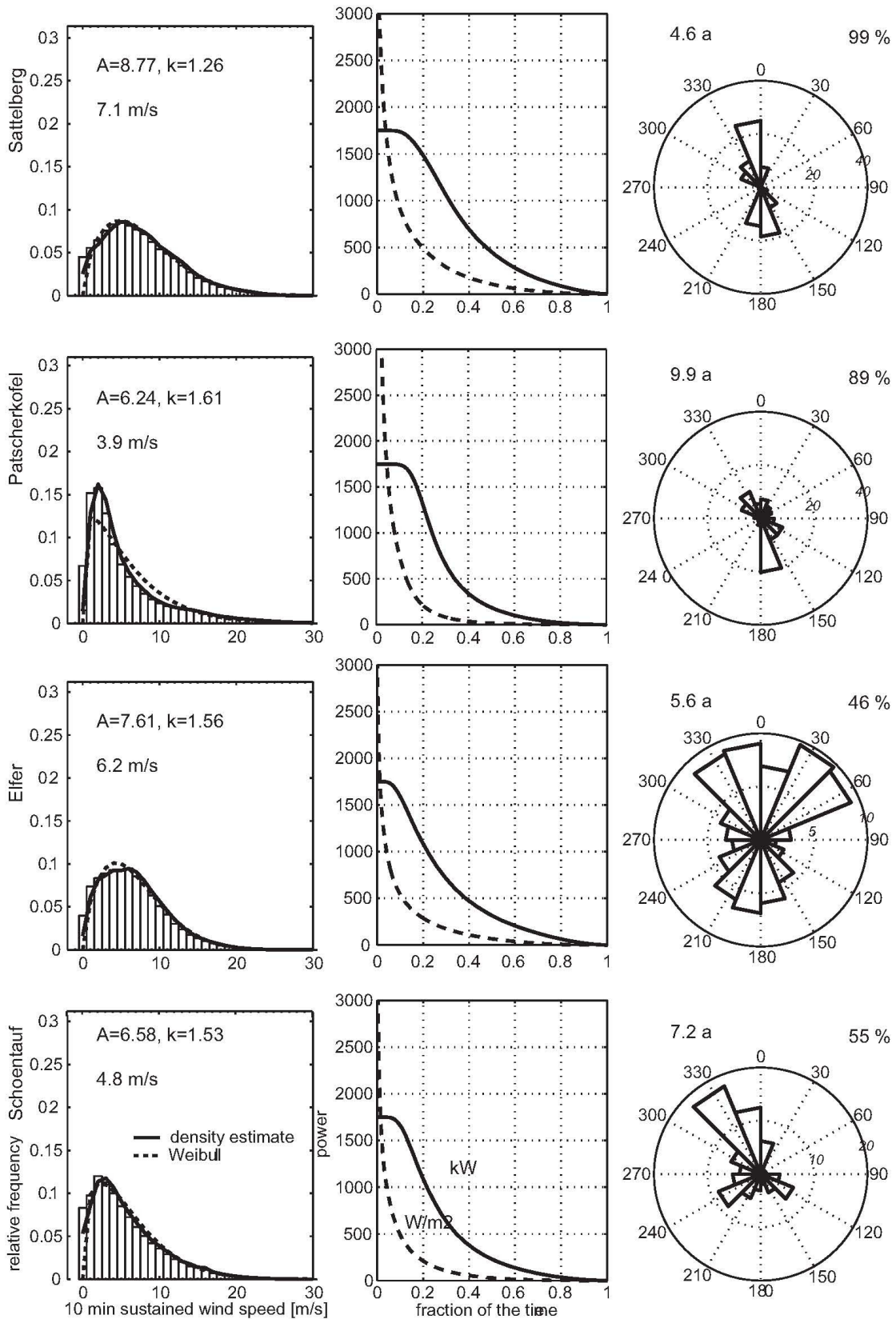


Figure 5: Topographical map (shading interval 500 m) of all the evaluated stations. The best potential wind energy sites are indicated with the labels SB = Sattelberg, SJ = Sandjoch, PA = Patscherkofel, ES = Elferspitze, SS = Schöntaufspitze. Names of valleys in light font. The black rectangle marks the region of the Wipp Valley (see chapter 3.2) with denser instrumentation for a period of 70 days. Inset shows the location of the map within central Europe.

## Appendix

Station	MSL [m]	Sensor [m] AGL	Median [m/s]	Weibull A [m/s]	k	In range [%]	Icing [%]	Median [W/m <sup>2</sup> ]	>=160 [%]	Extr. Pot. [kWh/(am <sup>2</sup> )]	Output [GWh/a]	Data [a]
SB	2108	3	7.1	8.8	1.62	79.7	3.5 *)	104	41.7	2927	5.23	4.59
SJ	2165	18	7.4	8.9	1.77	82.4	7.7 *)	117	42.6	2835	5.23	1.87
PA	2247	7	3.9	6.2	1.16	54.4	7.5	18	22.1	2673	3.01	9.85
ES	2926	4	6.2	7.6	1.65	75.9	29.4	67	31.7	1794	4.08	5.55
SS	3325	4	4.8	6.6	1.34	64.1	51.2	29	23.8	1612	3.32	7.18

Table 1: Station name (as in Fig. 5), altitude, height of the wind sensor above ground, median of the wind speed, Weibull parameters, the percentage of wind speed data that are within the operating range of common wind turbines between 3.5 and 25 m/s, the percentage of icing (relative to the missing data) of the potential wind energy sites, where \*) indicates that the icing relates to the prequality controlled data set with higher resolution data and refers to the whole time series of available data, Extractable power (median), percentage of extractable power above 160 W/m<sup>2</sup>, extractable wind energy potential and GWh/a with an exemplary wind turbine and the period of the available data. For the characteristics of the rest of the evaluated sites see [5].



**Figure 6: Wind statistics of the 4 stations of the Tyrolean routine networks with the highest wind energy potential: Sattelberg, Patscherkofel, Eiferspitze and Schöntaufspitze. (Left) Histogram and kernel-density fitted probability density function (solid) with fitted parametric Weibull distribution (dashed;  $A$  and  $k$ ) and median value (m/s); (center) power curves indicating the extractable power duration curve (dashed,  $W/m^2$  and the machine productivity curve (solid, kW); (right) wind rose with measurement period(years) and data availability (%). NB: different frequency scale (%; italics) among the stations.**