Near-Surface Wind-Speed Stilling in Alaska during 1984-2016 and Its Impact on the Sustainability of Wind Power

Gerhard Kramm1*, Nicole Mölders2, John Cooney3, Ralph Dlugi4

1Engineering Meteorology Consulting, Fairbanks, AK, USA
2Department of Atmospheric Sciences and Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, USA
3Department of Atmospheric Sciences, Texas A&M University, College Station, TX, USA
4Arbeitsgruppe Atmosphärische Prozesse (AGAP), Munich, Germany

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Abstract

Based on wind-speed records of Alaska’s 19 first-order weather stations, we analyzed the near-surface wind-speed stilling for January 1, 1984 to December 31, 2016. With exception of Big Delta that indicates an increase of 0.0157 m·s⁻¹·a⁻¹, on average, all other first-order weather stations show declining trends in the near-surface wind speeds. In most cases, the average trends are less than −0.0300 m·s⁻¹·a⁻¹. The strongest average trend of −0.0500 m·s⁻¹·a⁻¹ occurred at Homer, followed by −0.0492 m·s⁻¹·a⁻¹ at Bettles, and −0.0453 m·s⁻¹·a⁻¹ at Yakutat, while the declining trend at Barrow is marginal. The impact of the near-surface wind-speed stilling on the wind-power potential expressed by the wind-power density was predicted and compared with the wind-power classification of the National Renewable Energy Laboratory and the Alaska Energy Authority. This wind-power potential is, however, of subordinate importance because wind turbines only extract a fraction of the kinetic energy from the wind field characterized by the power efficiency. Since wind turbine technology has notably improved during the past 35 years, we hypothetically used seven currently available wind turbines of different rated power and three different shear exponents to assess the wind-power sustainability under changing wind regimes. The shear exponents 1/10, 1/7, and 1/5 served to examine the range of wind power for various conditions of thermal stratification. Based on our analysis for January 1, 1984 to December 31, 2016, Cold Bay, St. Paul Island, Kotzebue, and Bethel would be very good candidates for wind farms. To quantify the impact of a changing wind regime on wind-power sustainability, we predicted wind power for the periods January 1, 1984 to December 31, 1994 and January 1, 2006 to December 31, 2016.
as well. Besides Big Delta that suggests an increase in wind power of up to 12% for 1/7, predicted wind power decreased at all sites with the highest decline at Annette (≈38%), Kodiak (≈30%), King Salmon (≈26%), and Kotzebue (≈24%), where the effect of the shear exponents was marginal. Bethel (up to 20%) and Cold Bay (up to 14%) also show remarkable decreases in predicted wind power.

**Keywords**

Near-Surface Wind Speed, Wind Power, Wind-Power Potential, Wind-Power Density, Wind-Speed Stilling, Energy Flux Budget, Sensible and Latent Heat

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### 1. Introduction

There is observational evidence of declining trends in the near-surface wind speeds over the last five decades in numerous areas of the world [1]. Decreases in wind speeds have occurred, for instance, in Australia [2] [3], United States [4] [5] [6], China [7] [8] [9], Italy [10], Canada [11] [12], Spain and Portugal [13] [14], Alaska [15] [16], Canary Islands [17], and other locations in Europe and Asia [6]. Roderick et al. [3] already termed these declining trends as “stilling”.

McVicar et al. [1] analyzed 148 studies reporting terrestrial trends of the wind speed at anemometer height, $v_r = |v_\|$, from across the globe (with uneven and incomplete spatial distribution and differing periods of measurement). They found an average trend of $-0.014 \text{ m} \cdot \text{s}^{-1} \cdot \text{a}^{-1}$ for studies with more than 30 sites with observing data for more than 30 years. Assuming, for instance, a linear trend, these declining trends constitute a $-0.70 \text{ m} \cdot \text{s}^{-1}$ change in $v_r$ over 50 years [1]. Their review (a) gives evidence that terrestrial stilling is widespread across the globe; (b) confirms declining rates of evaporative demand, and (c) highlights the contribution $v_r$ has made to these declining evaporative rates. The terrestrial stilling has been attributed to various causes (e.g., [1] [13] [14], and the relevant references therein). The exact causes, however, have not yet been identified [17].

Terrestrial stilling is, however, not omnipresent. Some positive trends were reported by McVicar et al. [1]. The situation is rather complex as indicated by the observations performed at the first-order weather station Barrow (now the City of Utqiaġvik), Alaska (for the specification, see Table 1). Based on the period 1921-2001, Lynch et al. [18] found a positive trend of $0.0047 \text{ m} \cdot \text{s}^{-1} \cdot \text{a}^{-1}$. In addition, Hartmann and Wendler [16] found an increase in wind speed of 0.4 $\text{ m} \cdot \text{s}^{-1} \cdot \text{a}^{-1}$ when comparing period 1951 - 1975 with that of 1977 - 2001 related by these authors to the 1976 Pacific climate shift when the Pacific Decadal Oscillation index changed from the mainly negative values during the first 25-year period to the mainly positive values during the second one. On the contrary, we found a marginal decrease for the period January 1, 1984 to December 31, 2016 denoted as Period I hereafter. Nonetheless, the worldwide evidence for declining
near-surface wind speeds and their impact on the sustainability of wind power
demands care and attention.

The objective of our paper is two-fold: (a) to provide additional evidence to
the process of near-surface wind-speed stilling in Alaska during Period I, and (b)
to quantify the impact of a changing wind regime on the wind-power sustaina-
ble in the statewide region by considering the change from the period January
1, 1984 to December 31, 1994 denoted as Period II hereafter to the period January
1, 2006 to December 31, 2016 denoted as Period III hereafter. This means
that the Period I was divided into three equal periods of 11 years.

To achieve these goals, we consider Alaska’s 19 first-order weather stations
as a testbed. First-order stations are defined as those operated by certified ob-
servers and are typically operated by the National Weather Service. These sites
include a full suite of equipment to measure air pressure and temperature,
cloudiness, total precipitation, snowfall, wind speed and wind direction (e.g.
[16]). These stations are grouped into climate regions and their specifications
are listed in Table 1.

Declining trends in the near-surface wind speeds notably affect the wind-
power potential [6] commonly expressed by the wind-power density \(\text{i.e., the}
mean kinetic energy stream density} at a certain height above the surface [19],

\[
\overline{S_{\text{kin}}} = \frac{\rho}{2} \left( \overline{\overline{v^2}} + \overline{v'^2} \right) \overline{v} + \frac{1}{2} \rho \overline{v'^2} v'^2, \tag{1.1}
\]

This equation describes the transfer of mean kinetic energy (MKE) and tu-
rbulent kinetic energy (TKE) by the mean wind field and the transfer of TKE by
the eddying wind field. Here, \(\rho\) and \(v\) are the air density and the velocity of
the wind field at the same height, respectively. The overbar (\(\overline{\ldots}\)) characterizes
the conventional Reynolds mean and a prime (\(\prime\)) the deviation from that. The
hat (\(\hat{\ldots}\)) denotes the density-weighted average according to Hesselberg [20] de-
defined by

\[
\hat{\chi} = \frac{\overline{\overline{\rho \chi^2}}}{\rho}, \tag{1.2}
\]

and the double prime (\(''\)) marks the departure from that. Here, \(\chi\) is a field
quantity like the wind vector, \(v\), and the specific humidity \(m_1\). It is obvious
that \(\overline{\overline{\rho \chi^2}} = \rho \overline{\rho \chi^2} = 0\). Hesselberg’s average can be related to that of Reynolds by
[21] [22] [23] [24] [25].

\[
\hat{\chi} = \chi + \frac{\rho \overline{\rho \chi^2}}{\rho^2} = \chi \left[ 1 + \frac{\rho \overline{\rho \chi^2}}{\rho^2} \right]. \tag{1.3}
\]

Obviously the different means \(\hat{\chi}\) and \(\overline{\overline{\chi}}\), are nearly equal if \(\left| \rho \overline{\rho \chi^2}/\overline{\rho \chi^2} \right| \ll 1\)
as used, for instance, in case of the Boussinesq approximation. The Hesselberg
average of the wind vector, for instance, is given by \(\hat{v} = \overline{\overline{\rho v^2}}/\rho\). Note that inten-
sive quantities like air pressure, \(p_\text{s}\), and air density, \(\rho\), are averaged in the
sense of Reynolds. Arithmetic rules are given by [21] [23] [26] [27]. Hesselberg’s
Table 1. Specifications of the first-order stations of the National Weather Service in Alaska, USA, where \( z_e \) is the anemometer height.

| Station and ID Numbers | Location            | Latitude     | Longitude    | Elevation (m) | \( z_e \) (m) |
|------------------------|---------------------|--------------|--------------|---------------|--------------|
| 1 USW00027502          | Barrow WSO          | 71.2883°N    | 156.7814°W   | 9.4           | 8            |
| 2 USW00026533          | Bettles             | 66.9161°N    | 151.5089°W   | 195.7         | 10           |
| 3 USW00026411          | Fairbanks INTL      | 64.8039°N    | 147.8761°W   | 131.7         | 10           |
| 4 USW00026415          | Big Delta FAA/AMOS  | 63.9944°N    | 145.7214°W   | 389.2         | 10           |
| 5 USW00026510          | McGrath             | 62.9575°N    | 155.6103°W   | 101.5         | 10           |
| 6 USW00026425          | Gulkana             | 62.1592°N    | 145.4589°W   | 476.1         | 10           |
| 7 USW00026616          | Kotzebue WSO        | 66.8667°N    | 162.6333°W   | 9.1           | 8            |
| 8 USW00026617          | Nome WSO            | 64.5111°N    | 165.4400°W   | 4             | 8            |
| 9 USW00026615          | Bethel              | 60.7850°N    | 161.8292°W   | 31.1          | 8            |
| 10 USW00026528         | Talkeetna           | 62.3200°N    | 150.0950°W   | 106.7         | 8            |
| 11 USW00026451         | Anchorage INTL      | 61.1689°N    | 150.0278°W   | 36.6          | 8            |
| 12 USW00025507         | Homer               | 59.6419°N    | 151.4908°W   | 19.5          | 8            |
| 13 USW00025503         | King Salmon         | 58.6794°N    | 156.6294°W   | 19.2          | 10           |
| 14 USW00025339         | Yakutat             | 59.5119°N    | 139.6711°W   | 10.1          | 10           |
| 15 USW00025309         | Juneau              | 58.3567°N    | 134.5639°W   | 4.9           | 10           |
| 16 USW00025308         | Annette WSO         | 55.0389°N    | 131.5786°W   | 33.2          | 10           |
| 17 USW00025713         | St. Paul Island     | 57.1553°N    | 170.2222°W   | 10.7          | 10           |
| 18 USW00025501         | Kodiak              | 57.7511°N    | 152.4856°W   | 24.4          | 10           |
| 19 USW00025624         | Cold Bay            | 55.2208°N    | 162.7325°W   | 23.8          | 10           |

Density-weighted averaging procedure is well appropriate to formulate the balance equation for turbulent systems [19] [21] [23] [24] [26]-[33].

Ignoring in Equation (1.1) the turbulent effects yields

\[
\frac{2}{\rho} \mathbf{v} = \frac{2}{\rho} \mathbf{v} \cdot \nabla \mathbf{v}.
\]  

(1.4)

The magnitude of \( \mathbf{v} \) is given by

\[
\mathbf{v} = \left[ \frac{2}{\rho} \mathbf{v} \cdot \nabla \right] = \frac{2}{\rho} \mathbf{v}^3 = \frac{2}{\rho} \mathbf{v}^3,
\]  

(1.5)

where \( \mathbf{v} = \left[ \frac{2}{\rho} \mathbf{v} \cdot \nabla \right] \). Apparently, the wind-power density is proportional to the cube of wind speed. The rotor of a wind turbine causes a divergence effect expressed by \( \nabla \cdot \mathbf{v} \neq 0 \). The wind speed is usually assumed as uniformly distributed over the rotor area of a wind turbine which is a crude assumption. Generally, at a given location, all these quantities vary with time.

As wind turbines only extract a fraction of the kinetic energy from the wind field characterized by the power efficiency (see, e.g., [19] [34] and Figure 1),

\[
C_p = \frac{P}{P_{\infty}},
\]  

(1.6)
the wind-power potential is of subordinate importance. Here, $P$ is the extracted
(or consumed) power, and

$$P_{\infty} = \frac{1}{2} \rho A_R v_{\infty}^3 = A_R S_{\infty, \infty},$$

(1.7)
is the power carried by the flow through the projection of the turbine section re-
gion onto the plane perpendicular to it, where $v_{\infty}$ is the undisturbed wind
speed far upstream of the wind turbine, and $A_R$ is the rotor area considered as
perpendicular to the flow axis.

Therefore, it is indispensable to analyze how wind turbines respond to the de-
clining trends in near-surface wind speeds. Since the wind turbine technology
has notably improved during the past 35 years, we followed Mölders et al. [15]
and used seven currently available wind turbines of different rated power to as-
ssess the wind-power sustainability under changing wind regimes. These wind tur-
bines are: Enercon E-48, Suzlon S64 Mk II-1.25 MW, General Electric 1.6 - 82.5,
Senvion MM92 (formerly known as RE Power MM92), Mitsubishi MWT95/2.4,
Enercon E-82 E4, and Siemens SWT-3.6-107. They were chosen because their
rated power increases by an increment of about 400 kW. Some of their technical
specifications are listed in Table 2. Senvion MM92 and Mitsubishi MWT95/2.4
were also used by Mölders et al. [35] in their study on the uncertainty in wind-
power assessment over complex terrain.

In Section 2, we describe the data source and the methodology. Here, we also
compare the wind-power potential obtained from daily mean averages of wind
speed with that based on hourly mean averages of wind speed for the same time
interval because the latter is generally larger than the former. This comparison
serves for assessing the results of our wind-power predictions for the Periods I,
II, and III that are based on daily mean averages of wind speed taken from the
Global Historical Climatology Network (GHCN)-Daily [36]. The impact of the
Table 2. Specifications of the wind turbines considered in this study (adopted from Kramm et al. [19]).

| Wind turbine          | Hub height (m) | Swept area (m²) | Cut-in wind speed (m·s⁻¹) | Rated wind speed (m·s⁻¹) | Cut-out wind speed (m·s⁻¹) | Rated power (kW) | Wind Class |
|-----------------------|----------------|-----------------|---------------------------|--------------------------|---------------------------|-----------------|------------|
| Enercon E-48          | 76             | 1810            | 2-3                       | 13.5                     | 25                        | 800             | IEC IIa    |
| Suzlon S64 Mark II-1.25 MW | 74.5           | 3217            | 4                         | 12.0                     | 25                        | 1250            | IIa        |
| General Electric 1.6-82.5 | 80            | 5345            | 3.5                       | 11.5                     | 25                        | 1600            | IEC IIIb   |
| Senvion MM92          | 78-80          | 6720            | 3                         | 12.5                     | 24                        | 2050            | IEC IIa    |
| Mitsubishi MWT95/2.4  | 80             | 7088            | 3                         | 12.5                     | 25                        | 2400            | IEC IIa    |
| Enercon E-82 E4       | 78/84          | 5281            | 2-3                       | 16                       | 25                        | 3000            | IEC IIa    |
| Siemens SWT-3.6-107   | 80             | 9000            | 3                         | 14.0                     | 25                        | 3600            | IEC Ia     |

near-surface wind-speed stilling on the energy conversion at the interface Earth-atmosphere and the wind power is analyzed in Section 3. Note that the decreasing evapotranspiration as reported by McVicar et al. [1] also affects the energy conversion at the interface Earth-atmosphere. Our method to predict the wind power using the seven currently available wind turbines of different rated power listed in Table 2 is outlined in Section 4. The results are presented in Section 5.

2. Wind Data and Methodology

To estimate the wind-power potential in Alaska, we considered the daily mean wind data provided by the 19 first-order weather stations in Alaska for Periods I, II, and III. The wind data are taken from the Global Historical Climatology Network (GHCN)-Daily [36]. Days for which no wind data were reported were removed from the datasets. The number of days considered is listed in Table 3. Anemometer heights were taken from http://www.nws.noaa.gov/ops2/Surface/documents/windtower.xls.

Based on these wind data, we assessed these locations for their suitability for wind farms by answering three major questions:

1) Does the location exhibit enough wind speed to generate electrical power in a sufficient manner?

2) Is this electrical power affected by long-term trends in horizontal wind speeds?

3) Are there obstacles such as siting issues present at the location?

The first two questions relate to the basic requirements for establishing a wind farm. The third question assesses the impacts of any kind of energy producing facilities (e.g., power plants fueled with coal, oil, gas, or nuclear elements to hydropower systems, wind farms) on the natural environment. The impact of wind farms on endangered species, avian migrations/habitats, wetlands/protected areas, and subsistence lifestyle must be considered as well. Additionally, for numerous Alaska areas, the ambient temperatures fall below −20˚C in winter which is below the operation range of most wind turbines, except cold climate versions like that of Senvion MM92 which has a lower limit of −30˚C. Frequently icing of rotor blades due to the occurrence of supercooled
water in the lower atmospheric boundary layer may affect the outcome of wind power as well. The answers to these questions served as the foundation for evaluating each site in terms of cost-benefits analyses.

First, we analyzed whether the wind speeds observed at a given location during the period under study satisfy the minimum average wind speed requirement. A site must have a minimum annual average wind speed of, at least 4.9 m/s to 5.8 m/s to be considered (American Wind Energy Association, 2009).

The average $\langle v_R \rangle$ for each station was calculated using

$$
\langle v_R \rangle = \frac{1}{T_N} \int \frac{T_d}{T_N} v_{R,1} (t) \, dt + \frac{1}{T_d} \int v_{R,2} (t) \, dt + \cdots + \frac{1}{T_d} \int v_{R,N} (t) \, dt,
$$

where $t$ is time, $T_N = NT_d$ is the period under study, $N$ is the number of days, $T_d = T_i - T_{i-1}, i = 1, 2, \cdots, N$, is the time period of a day, and $v_R (t) = \left| v_R (t) \right|$ is the time-dependent horizontal wind speed at anemometer height that usually amounts to $z_R \approx 10$ m ($\approx 33$ ft) above the surface. At seven of the 19 first-order stations, wind speed is measured at a height of $z_R \approx 8$ m ($\approx 26$ ft). For all first-order stations, linear trends in daily mean wind speeds are listed in Table 3 for Period I.

Equation (2.1) provides the average wind speed for each station. Introducing the daily mean wind speed by

$$
\bar{v}_{R,i} = \frac{1}{T_d} \int_{T_{i-1}}^{T_i} v_{R,i} (t) \, dt,
$$

where $v_{R,i} (t)$ is the wind speed at anemometer height for the time $T_{i-1}, T_i$ of the $i^{th}$ day, leads to

$$
\langle v_R \rangle = \frac{1}{N} \sum_{i=1}^{N} \bar{v}_{R,i}.
$$

As described in the Wind Energy Resource Atlas of the United States, another measure for assessing the wind-power potential at a given location is related to the wind-power class listed in Figure 2. It is based on the true wind-power density at the height of $z = 50$ m above ground. The average of the wind-power density is given by

$$
\langle S_{\text{kin},z} \rangle = \frac{1}{2T_N} \int_{0}^{T_d} \rho_z (t) v_z^2 (t) \, dt.
$$

Here, $\rho_z (t)$ is the air density, and $v_z (t)$ is the wind speed at $z$. Similar to Equation (2.1), we obtain

$$
\langle S_{\text{kin},z} \rangle = \frac{T_d}{2T_N} \left( \int_{T_{i-1}}^{T_i} \rho_{z,1} (t) v_{z,1}^2 (t) \, dt + \int_{T_d}^{T_i} \rho_{z,2} (t) v_{z,2}^2 (t) \, dt + \cdots + \int_{T_d}^{T_N} \rho_{z,N} (t) v_{z,N}^2 (t) \, dt \right)
$$

where $\rho_{z,i} (t)$ and $v_{z,i}^2 (t)$ are related to the time of the $i^{th}$ day.
Table 3. Average wind speed, \( \langle v_z \rangle \), and change in wind speed expressed (a) by a linear trend, \( \Delta v_{z,a} \), and (b) by the Period I-averaged change, \( \Delta v_{z,P} \), at first-order stations of the National Weather Service in Alaska, USA, where \( N \) is the number of days used in our analysis.

| Location               | \( N \)  | \( \langle v_z \rangle \) m\( \cdot \)s\(^{-1} \) | \( \Delta v_{z,a} \) m\( \cdot \)s\(^{-1} \)\( \cdot \)a\(^{-1} \) | \( \Delta v_{z,P} \) m\( \cdot \)s\(^{-1} \) |
|------------------------|---------|----------------------------------|----------------------------------|-----------------|
| Barrow WSO             | 12,011  | 5.63                             | -0.0001                          | -0.03           |
| Bettles                | 11,629  | 2.43                             | -0.0492                          | -1.62           |
| Fairbanks INTL         | 12,019  | 1.97                             | -0.0368                          | -1.21           |
| Big Delta FAA/AMOS     | 11,333  | 4.13                             | 0.0157                           | 0.52            |
| McGrath               | 12,031  | 2.00                             | -0.0405                          | -1.33           |
| Gulkana                | 11,552  | 2.51                             | -0.0443                          | -0.14           |
| Kotzebue WSO           | 12,023  | 5.24                             | -0.0395                          | -1.30           |
| Nome WSO               | 11,991  | 4.18                             | -0.0221                          | -0.73           |
| Bethel                 | 12,052  | 5.22                             | -0.0269                          | -0.89           |
| Talkeetna              | 11,914  | 2.01                             | -0.0389                          | -1.28           |
| Anchorage INTL         | 12,052  | 3.10                             | -0.0310                          | -1.02           |
| Homer                  | 12,033  | 3.14                             | -0.0500                          | -1.65           |
| King Salmon            | 12,054  | 4.33                             | -0.0313                          | -1.03           |
| Yakutat                | 12,039  | 2.52                             | -0.0453                          | -1.50           |
| Juneau                 | 11,556  | 3.33                             | -0.0205                          | -0.68           |
| Annette WSO            | 12,047  | 3.56                             | -0.0426                          | -1.40           |
| St. Paul Island        | 11,990  | 6.92                             | -0.0173                          | -0.57           |
| Kodiak                 | 12,049  | 4.84                             | -0.0450                          | -1.48           |
| Cold Bay               | 12,051  | 7.19                             | -0.0391                          | -1.29           |

Introducing the respective daily mean value of this true wind-power density by

\[
\bar{S}_{kin,z,d} = \frac{1}{2T_d} \int_{t_{i-1}}^{t_i} \rho_{z,d} (t) v_{z,d}^3 (t) \, dt
\]  

(2.6)

provides

\[
\langle \bar{S}_{kin,z} \rangle = \frac{1}{N} \sum_{i=1}^{N} \bar{S}_{kin,z,d}.
\]  

(2.7)

Unfortunately, the wind speed data taken from the GHCN-Daily do not allow to precisely compute \( \bar{S}_{kin,z,d} \). Even if we consider air density as nearly constant for the \( i^{th} \) day (which leads to the so-called anelastic approximation of the equation of continuity), we have to acknowledge that

\[
\left( v_{z,i} \right)^3 \leq v_{z,d}^3.
\]  

(2.8)

This inequality can be verified using Hölder’s inequality for integrals,
The annual wind power estimates for this map were produced by AWS TruePower using their MesoMap system and historical weather data. It has been validated with available surface data by NREL. The data is still under review by the AEA and subject to change.

Figure 2. Wind-power classification according to National Renewable Energy Laboratory and the Alaska Energy Authority.

\[
\int_{a}^{b} f(x) g(x) \, dx \leq \left( \int_{a}^{b} f(x)^{p_h} \, dx \right)^{\frac{1}{p_h}} \left( \int_{a}^{b} g(x)^{q_h} \, dx \right)^{\frac{1}{q_h}},
\]

where \( p_h \in (1, \infty) \) and \( q_h \) are conjugate exponents obeying

\[
\frac{1}{p_h} + \frac{1}{q_h} = 1,
\]

i.e., \( q_h = \frac{p_h}{(p_h - 1)} \). Furthermore, \( f(x) \) and \( g(x) \) are real functions \((f, g: [a, b] \rightarrow \mathbb{R})\). For the two non-negative measurable functions \( f(x) = v_{z,i}(x) \) and \( g(x) = 1 \) as well as \( p_h = 3 \Rightarrow q_h = 3/2 \), and \( x = t/T_d \), we obtain

\[
\overline{v_{z,i}} = \frac{1}{T_d} \int_{0}^{T_d} v_{z,i}(x) \, dx \leq \left( \int_{0}^{T_d} \overline{v_{z,i}^2}(x) \, dx \right)^{\frac{1}{2}} = \left( \overline{v_{z,i}^2} \right)^{\frac{1}{2}}
\]

and in a further step the Inequality (2.8). Differences

\[
\Delta v^3 = \frac{v_{z,i}^3 - \overline{v_{z,i}^3}}{v_{z,i}^3}
\]

are illustrated in Figure 3 and Figure 4 for two different cases. Figure 3 is based
Figure 3. Time series of the relative difference $\Delta v^3$ in wind-power density (given by Equation (2.12)) representative for the height interval from 64 m to 113 m above ground level (black line). The hourly wind speed data stem from WRF/chem model simulations performed for the area of the Eva Creek wind farm in Interior Alaska for October 1, 2008 to April 1, 2009 ([38] [34]). The blue line indicates the mean value of $\Delta v^3 = 23.3\%$.

Figure 4. As in Figure 3, but the hourly mean wind speeds are related to the measurements performed at first-order weather station Bethel (anemometer height of $z_0 = 8$ m (26 ft)). The corresponding daily mean wind speeds illustrated in Figure 5 covered the period from January 1, 1979 to December 31, 1983. The blue line indicates the mean value of $\Delta v^3 = 21.9\%$.

on WRF/chem model simulations performed for the area of the Eva Creek wind farm in Interior Alaska. This mean wind speed is representative for heights between 64 and 113 m above ground level [34] [37]. Daily mean wind speeds were
computed using hourly mean wind speeds. The figure shows that the Inequality (2.8) is always fulfilled.

**Figure 4** is based on the hourly mean wind speeds related to observations at Bethel (anemometer height of \( z_R = 8 \text{ m (26 ft)} \)) from January 1, 1979 to December 31, 1983. Missing data were replaced by interpolated values to obtain an adequate dataset of daily mean wind speeds (**Figure 5**). Nevertheless, 70 of these daily mean wind speeds were removed from the dataset because of too many missing hourly mean wind speeds. Apparently, these daily mean wind speeds decreased. Again, the Inequality (2.8) is always fulfilled. Since the wind-power potential is of subordinate importance, we analyze how the chosen wind turbines (see **Table 2**) respond to this difference in the wind-power potential (see Section 5).

The daily mean wind speed, \( \overline{v}_{R,i} \), is based on observations performed at anemometer height \( z_R \). To compute the mean wind speed at higher levels than the anemometer height, \( z > z_R \), commonly the power-law profile (e.g., \[38\] \[39\] \[40\] \[41\] \[42\]),

\[
\overline{v}_{z,i} = \overline{v}_{R,i} \left( \frac{z}{z_R} \right)^{\frac{\rho_i}{\rho_f}},
\]

is used, where \( \overline{v}_{z,i} \) and \( \overline{v}_{R,i} \) are the wind speeds at the heights \( z \) and \( z_R \), respectively. Here, the shear exponent ranges from \( p_i = 1/7 \) for near-neutral stability conditions to \( p_i = 1/10 \) for strong lapse rates. Frost \[43\] reported that for extremely stable stratification, \( p_i = 8/10 \) may be possible. Generally, \( p_i \) varies in the diurnal course and depends on the surface roughness and the height of the level under evaluation (e.g., \[40\] \[41\] \[43\] \[44\] \[45\] \[46\]). Based on the study

![Figure 5](https://example.com/image5.png)

**Figure 5.** Daily mean wind speeds (black line) related to the measurements at the anemometer height of \( z_R = 8 \text{ m (26 ft)} \) at Bethel for January 1, 1979 to December 31, 1983. The red line illustrates the linear trend. Daily mean wind speeds were computed from hourly mean wind speeds.
of Schwartz and Elliot regarding the wind shear characteristics at Central Plains (Texas to North Dakota) tall towers [40], we used \( p_i = 1/5 \) as an upper limit.

Since \( v_{R,i} \) for the \( i^{th} \) day is given by

\[
\begin{aligned}
\overline{v_{R,i}} &= \frac{1}{T_d} \int_0^{T_d} v_{R,i}(t) \, dt \\
&= \frac{\Delta T}{T_d} \left( \frac{1}{\Delta T} \int_0^{\Delta T} v_{R,i}(t) \, dt + \frac{1}{\Delta T} \int_{\Delta T}^{2\Delta T} v_{R,i}(t) \, dt + \cdots + \frac{1}{\Delta T} \int_{(M-1)\Delta T}^{M\Delta T} v_{R,i}(t) \, dt \right)
\end{aligned}
\]  

(2.14)

where \( \Delta T = T_k - T_{k-1} \), \( k = 1, 2, \cdots, M \), \( T_0 = 0 \), and \( T_M = M\Delta T \). \( M \) is the number of averaging intervals, for instance, of \( \Delta T = 30 \text{ min} \) or \( \Delta T = 60 \text{ min} \). The mean wind speed for the \( k^{th} \) averaging interval is then given by

\[
\overline{v_{R,i,k}} = \frac{1}{\Delta T} \int_{T_{i,k}}^{T_{i,k+1}} v_{R,i,k}(t) \, dt.
\]

(2.15)

Thus, we obtain

\[
\overline{v_{R,i}} = \frac{1}{M} \sum_{k=1}^{M} \overline{v_{R,i,k}}.
\]

(2.16)

In accord with Equation (2.13), the corresponding wind speed at \( z \) amounts to

\[
\overline{v_{z,i}} = \frac{1}{M} \sum_{k=1}^{M} \overline{v_{R,i,k}} \left( \frac{z}{z_R} \right)^{p_{z,i,k}}.
\]

(2.17)

In case of an exponent \( p_{z,i,k} \) that does not vary with time during the \( i^{th} \) day, i.e., \( p_{z,i,k} = p_i \), one obtains Equation (2.13). This equation was used to extrapolate the daily mean wind speeds at \( z_R \) to both the level of \( z = 50 \text{ m} \) to compute the wind-power density, \( \langle S_{\text{kin,z}} \rangle \), of the wind field as express by Equation (2.4) and of \( z = 80 \text{ m} \) chosen as the hub height of the wind turbines considered in this study. For each first-order weather station, we considered \( p = p_i = 1/10 \), \( p = p_i = 1/7 \), and \( p = p_i = 1/5 \) to cover the range of wind power for various conditions of thermal stratification. Based on these shear exponents, vertical wind profiles were drawn, where \( p = p_i = 1/10 \) causes the weakest and \( p = p_i = 1/5 \) produces the strongest increase of wind speed with height (Figure 6). Thus, the assumption that the wind speed is uniformly distributed over the rotor area of a wind turbine is rather crude. In situations with strong wind shear, the turbine blades, shaft and roller bearing of the rotor may notably be affected by varying thrust forces during each rotation. Thus, high values of \( p \) imply that wind turbines can generate a substantial amount of energy, even when the wind speed near the ground is minimal. Concurrently, larger values of \( p \) will introduce higher fatigue loads on the turbine blades [41] [42] [47] [48].

Figure 7 shows the average wind speed determined for each first-order weather station,

\[
\langle v_z \rangle = \frac{1}{N} \sum_{i=1}^{N} \overline{v_{z,i}}.
\]

(2.18)

at both \( z = 50 \text{ m} \) and \( z = 80 \text{ m} \).
The respective mean wind-power density $\langle S_{\text{kin}, z} \rangle$ (see Equation (2.4)) at these heights is illustrated in Figure 8. According to these figures and the wind-power classification listed in Figure 2, we do not further consider sites that are related to a wind-power class of 1 (termed as “poor”) like Bettles (2), Fairbanks (3), McGrath (5), Gulkana (6), Talkeetna (10), Anchorage (11), Homer (12), and Yakutat (14) in our wind-power analysis, despite their declining trends in the near-surface wind speed. These stations would be impractical options for wind farms because they were unable to meet the basic criteria. The wind speeds at these locations would not be high enough to sufficiently supply power to the...
surrounding cities and communities, respectively. In most cases, the average trends are less then −0.0300 m∙s⁻¹∙a⁻¹, with exception of Gulkana that only exhibits a value of −0.0043 m∙s⁻¹∙a⁻¹ (Table 3). The strongest trend occurred at Homer with −0.0500 m∙s⁻¹∙a⁻¹, on average, followed by Bettles with −0.0492 m∙s⁻¹∙a⁻¹ and Yakutat with −0.0453 m∙s⁻¹∙a⁻¹ (Table 3). Thus, we only discuss the predicted wind-power outcomes obtained for Barrow (1), Big Delta (4), Kotzebue (7), Nome (8), Bethel (9), King Salmon (13), Juneau (15), Annette (16), St. Paul Island (17), Kodiak (18), and Cold Bay (19) in detail. Note that Cold Bay and St. Paul Island are related to the wind-power class of 6 (“outstanding”), followed by Kotzebue that is related to a wind-power class of 4 (“good”), Barrow, Bethel and Kodiak are related to a wind-power class of 3 (“fair”), Big Delta and Nome are related to a wind-power class of 2 (“marginal”). We only considered Juneau and Annette for the purpose of comparison with recent results [15]. Figure 9 shows the records of the daily mean wind speed at these weather stations for Period I.

The linear trends shown in Figure 9 indicate declining trends in the daily mean wind speeds, with exception of Big Delta that shows a positive one (Table 3). The decrease at Barrow is marginal. At all other first-order weather stations, such declining trends in the daily mean wind speed occurred as well (Table 3). However, this fact is of minor importance because \( \langle S_{lin} \rangle \) is already very low (Figure 8). Except for Barrow, all results are statistically significant according to a two-side t-test at 95% confidence.

We assess the impact on the sustainability of wind power by quantifying the change in the predicted wind power from Period II (January 1, 1984 to December 31, 1994) to Period III (January 1, 2006 to December 31, 2016).

3. The Impact of the Long-Term Wind-Speed Decrease on Energy Conversion at the Interface Earth-Atmosphere and Wind Power

The reasons for the long-term decrease of the mean horizontal wind speed as
Figure 9. Records of the daily mean wind (black lines) at first-order weather stations (a) Barrow, (b) Big Delta, (c) Kotzebue, (d) Nome, (e) Bethel, (f) King Salmon, (g) Juneau, (h) Annette, (i) St. Paul Island, (j) Kodiak, and (k) Cold Bay for Period I. Red lines illustrate the linear trends (see Table 1 for anemometer heights, z_e, at these stations).

documented by 18 of the 19 first-order weather stations in Alaska are unknown. This long-term decrease, however, may impact not only the generation of electricity using wind power, but also the near-surface air temperature. To address the latter, we considered the energy flux balance at the interface atmosphere assuming bare soil\(^1\) for simplification. For a given location (characterized, for instance, by the zenith angle, θ, and the azimuthal angle, φ) it reads (only the components normal to the horizontal surface element play a role)

\[
R_{\text{SR}}(\Theta_0, \theta, \varphi)(1-\alpha_s(\Theta_0, \theta, \varphi)) + e(\theta, \varphi)R_{\text{L}}(\theta, \varphi) - e(\theta, \varphi)\sigma T_\varepsilon(\theta, \varphi) - H(\theta, \varphi) - E(\theta, \varphi) + G(\theta, \varphi) = 0
\]  

(3.1)

Here, \(R_{\text{SR}}(\Theta_0, \theta, \varphi)\) is the global (direct plus diffusive solar) radiation, \(\Theta_0 = \Theta_0(\theta, \varphi)\) is local zenith angle of the Sun’s center, \(\alpha_s(\Theta_0, \theta, \varphi)\) is the albedo of the short-wave range, \(R_{\text{L}}(\theta, \varphi)\) is the down-welling long-wave radiation, \(e(\theta, \varphi) = 1 - \alpha_L(\theta, \varphi)\) [64] is the relative emissivity assumed to be equal to the absorptivity, \(\alpha_L(\theta, \varphi)\) is the albedo of the long-wave range, and

\(^1\)The inclusion of a vegetation canopy has been discussed, for instance, by Deardorff [49], McCumber [50] [51], Meyers and Paw U [52] [53], Sellers et al. [54], Braud et al. [55], Kramm et al. [56] [57], Ziemann [58], Su et al. [59], Pyles et al. [60] [61], and Mölders et al. [62] [63].
$T_s(\theta, \varphi)$ is the surface temperature. The quantities $H(\theta, \varphi)$ and $E(\theta, \varphi)$ are the fluxes of sensible and latent heat within the atmosphere caused by mainly molecular effects in the immediate vicinity of the Earth’s surface and by turbulent effects in the layers above. These fluxes are usually not directly measured, i.e., they have to be computed based on mean quantities derived from observations. Under horizontally homogeneous and steady-state conditions these fluxes can be parameterized by [39] (hereafter, $\theta$ and $\varphi$ are omitted)

$$H = -c_{p,0} \left( \frac{\rho \alpha_c}{C_p} \frac{\partial T}{\partial z} - \rho w^* \Theta^* \right)$$

(3.2)

and

$$E = -\lambda_{1,1} \left( \frac{\rho D_m}{C_m} \frac{\partial m}{\partial z} - \rho w^* m_s^* \right),$$

(3.3)

where the vertical components of the respective gradients characterize the molecular effects in accord with the laws of Fourier and Fick, respectively, and the covariance terms $\rho w^* \Theta^*$ and $\rho w^* m_s^*$ represent the turbulent effects. Here, $\alpha_c$ is the thermal diffusivity, $D_m$ is the diffusivity of the water vapor in air, and $\lambda_{1,1} = h_p - h_{js}$ is the specific heat of phase transition, where $\lambda_{s1}$ is the specific heat of vaporization, $\lambda_{s1}$ is the specific heat of sublimation, respectively. The fluxes of sensible and latent fluxes are usually parameterized by [39] [64]

$$H = -c_{p,s} C_h (U_R - U_s) \left( \Theta_R - \hat{T}_s \right) = \text{const.}$$

(3.4)

and

$$E = -\lambda_{s1} C_m (U_R - U_s) \left( m_{hs} - \hat{m}_{m,s} \right) = \text{const.},$$

(3.5)

where horizontally homogeneous and steady-state conditions are presupposed to fulfill the requirements of the Prandtl layer (also called the atmospheric surface layer, ASL, or the constant-flux layer), the lowest layer of the atmosphere of a thickness of about ten meters. Here, $U_R = \left[ \hat{v}_R \right]$ and $U_s = \left[ \hat{v}_s \right]$ are the mean horizontal wind speeds at $z_R$ (subscript R) and at the Earth’s surface (subscript s), where in the case of rigid walls (like layers of soil, snow, and/or ice) the latter is equal to zero, $\Theta_R$ is the potential temperature at $z_R$, $\hat{T}_s$ is the absolute temperature at the water surface, and $m_{hs}$ and $m_{m,s}$ are the corresponding values of the specific humidity. Furthermore, the potential temperature is defined by

$$\Theta = T \left( \frac{p_R}{p_s} \right)^k = \frac{T}{\pi},$$

(3.6)

where $\pi = (p_s / p_{s0})^k$ is the Exner-function, $p_s$ is the air pressure, and $p_{s0}$ is a reference pressure (usually $p_{s0} = 1000 \text{ hPa}$). The exponent $k$ is given by

$$k = \frac{R}{c_p} \left[ 1 + \frac{1}{c_{p,0}} \sum_{j=1}^{3} \frac{c_{p,j}}{1 + c_{p,0} - c_{p,j}} m_j \right].$$

(3.7)
Here, $R$ is the calculated gas constant for moist air, $R_0$ is the calculated gas constant for dry air, $R_1$ is the gas constant for water vapor, $c_p = \left( \frac{\partial h}{\partial T} \right)_{p,m,j} = \sum_{j=0}^{3} c_{p,j} m_j$ is the specific heat at constant pressure, $c_{p,j} = \left( \frac{\partial h_j}{\partial T} \right)_{p,m,j}$ is the partial specific heat at constant pressure, $m_j = \rho_j / \rho$ is the mass fraction, where $\rho_j$ is the partial density for dry air ($j = 0$), water vapor ($j = 1$), liquid water ($j = 2$), and ice ($j = 3$), respectively. These partial densities obey
\[ \sum_{j=0}^{3} m_j = 1 \Rightarrow m_0 = 1 - \sum_{j=1}^{3} m_j. \] (3.8)

Furthermore, $h$ is the specific enthalpy, and $h_j = \left( \frac{\partial h_j}{\partial m_j} \right)_{T,p}$ is the partial specific enthalpy. Moreover, $C_h$ and $C_m$ are the local transfer coefficients for sensible heat and water vapor, respectively, given by
\[ C_h = \frac{\kappa^2}{\left( \kappa \left( \frac{\xi}{2} \right) \right)^{1/2} + \ln \frac{z}{z_r} - \Psi_m \left( \zeta_R, \zeta_r \right) \left( \kappa B_h^{-1} + \ln \frac{z}{z_r} - \Psi_h \left( \zeta_R, \zeta_r \right) \right)} \] (3.9)
and
\[ C_m = \frac{\kappa^2}{\left( \kappa \left( \frac{\xi}{2} \right) \right)^{1/2} + \ln \frac{z}{z_r} - \Psi_m \left( \zeta_R, \zeta_r \right) \left( \kappa B_m^{-1} + \ln \frac{z}{z_r} - \Psi_m \left( \zeta_R, \zeta_r \right) \right)} \] (3.10)

where Panofsky's [65] integral similarity (or stability) functions for momentum (subscript $m$), sensible heat (subscript $h$), and water vapor (subscript $m_1$) are defined by (e.g., [25] [39] [66] [67])
\[ \Psi_{m,h,m_1} \left( \zeta_R, \zeta_r \right) = \int_{z_r}^{z} \frac{1 - \Phi_{m,h,m_1} \left( \frac{z}{L} \right)}{z} dz = \int_{z_r}^{\zeta_r} \frac{1 - \Phi_{m,h,m_1} \left( \zeta \right)}{\zeta_r} d\zeta. \] (3.11)

Here, $\kappa$ is the von Kármán constant, $\xi_d = 2 \left( \frac{u_*}{u_r} \right)^2$ is the local drag coefficient (e.g., [68]), $B_h$ and $B_m$ are the sublayer Stanton number for heat and the sublayer Dalton number for water vapor, respectively (e.g., [68]-[76]), and $u_r$ is the friction velocity defined by $u_r^2 = \left| \mathbf{r} \right| / \rho$, where $\mathbf{r}$ is the friction stress vector. Furthermore, $\Phi_m \left( \zeta \right)$, $\Phi_h \left( \zeta \right)$, and $\Phi_{m_1} \left( \zeta \right)$ are the local similarity functions for momentum, sensible heat, and water vapor, respectively. They are based on the similarity hypothesis of Monin and Obukhov [77]. These local similarity (or stability) functions are given by
\[ \Phi_m \left( \zeta \right) = \frac{z}{u_r \kappa} \frac{\hat{h}_m}{\hat{z}}, \] (3.12)
\[ \Phi_h \left( \zeta \right) = \frac{z}{\Theta_r \kappa} \frac{\hat{\Theta}}{\hat{z}}, \] (3.13)
\[ \Phi_m (\zeta) = \frac{z}{m_r \kappa} \frac{\partial m}{\partial z}, \quad (3.14) \]

where \( \zeta = z/L \) is the Obukhov number, \( \zeta_r = z_r/L \) and \( \zeta_R = z_R/L \) are the Obukhov numbers for the outer edge of the sublayer, \( z_r \), and for the top of the Prandtl layer, \( z_R \), and

\[ L = \frac{c_{p,0} \overline{\rho U^2}}{\kappa \frac{g}{\Theta} \left( H + 0.61 c_{p,0} \Theta \frac{E}{\lambda_{11}} \right)} \quad (3.15) \]

is the Obukhov stability length. Furthermore, \( c_{p,0} \) is the specific heat at constant pressure for dry air, \( U_H = \overline{u_H} \) is the mean horizontal wind speed, \( g \) is the acceleration of gravity, and \( \Theta \) is a potential temperature representative for the entire Prandtl layer.

To determine the local drag coefficient and the local similarity function for momentum, the magnitude of the friction stress vector,

\[ |\tau| = \rho C_D (U_R - U_i)^2 = \text{const.} \quad (3.16) \]

with

\[ C_D = \frac{\kappa^2}{\kappa^2 + \ln \frac{z_R}{z_r} - \Psi_m (\zeta_R, \zeta_r)} \quad (3.17) \]

and in a further step the friction velocity must be computed. Since the thermal stratification of the Prandtl layer varies in the diurnal cycle, the computation of \( |\tau| \) and \( u_t \) as well as \( H \) and \( E \) based on daily mean values of horizontal wind speed, temperature and humidity is, in general, a rather imperfect procedure. Despite the mean wind speed at the surface of rigid walls being zero, calculating of \( H \) and \( E \) over layers of bare soil, snow, and ice requires, at least, two vertical profile values of mean temperature and mean humidity, for instance, at \( z_R \) and at the surface. Since these surface values are usually unavailable, soil-vegetation-atmosphere-transfer (SVAT) schemes may be taken into consideration. Mölders et al. [63] [64], for instance, used the hydro-thermodynamic soil vegetation scheme (HTSVS) to predict the water budget elements (water supply to the atmosphere, groundwater recharge, and change in storage) for 2050 consecutive days (May 22, 1992 to December 31, 1997). They used routine data of hourly-mean values of horizontal wind speed, relative humidity, temperature, global radiation, and precipitation provided by a climate and lysimeter station at Brandis (south-east of Leipzig, Saxony) and evaluated the predicted water budget elements against the respective lysimeter data.

Assuming that \( \hat{v}(z) \) given by Equation (2.13) is equal to

\[ \hat{v}(z) = \frac{\mu_t}{\kappa} \left( \ln \frac{z}{z_0} - \Psi_m (\zeta, \zeta_0) \right) \quad (3.18) \]
yields [34] [78]

\[
p = \ln \left( \frac{z}{z_0} \right) - \Psi_m \left( \zeta, \zeta_0 \right) \left( \ln \left( \frac{z}{z_R} \right) - \Psi_m \left( \zeta_R, \zeta_0 \right) \right) - 1.
\]

(3.19)

This formula shows that the shear exponent explicitly depends on thermal stratification.

Equations (3.4) and (3.5) suggest that the decrease in the mean horizontal wind speed as demonstrated by the global stilling can reduce the fluxes of sensible and latent heat, and, according to Equation (3.1), can increase the surface temperature. The situation, however, is rather complex because a decrease of evapotranspiration also affects the formation and depletion of clouds and, subsequently, the scattering and absorption of solar radiation and the emission of infrared radiation by hydrometeors. Analyzing such interrelations requires the support by non-hydrostatic models of the meso-scales $\beta/\gamma$ [79]-[85].

Usually, MKE can be converted into TKE. In the inertial range, for instance, the TKE is transferred from lower to higher wave numbers until the far-dissipation range is reached, where kinetic energy is converted into heat energy by direct dissipation, $\bar{J} = \bar{V} \bar{v}$, and turbulent dissipation, $\bar{J} = \bar{\nabla} \bar{v} \bar{v}$, where $\bar{J}$ is the Stokes stress tensor [19]. Wind turbines may generate even more TKE. Heating of air due to the dissipation of TKE has been discussed and investigated (e.g., [86] [87] [88]). It has been assessed as being marginal.

The use of wind farms, however, will contribute to a further decrease of the mean horizontal wind speed [89] [90] [91] [92] [93] and may notably affect the energy conversion at the interface Earth-atmosphere either directly as described before or indirectly, for instance, by altering the cloudiness over and/or the lee-side regions of wind-farm areas [94].

The axial momentum theory [95] [96] [97], for instance, leads to the power efficiency [19]

\[
C_p = \frac{1}{2} \left( 1 + X \right) \left( 1 - X^2 \right).
\]

(3.20)

Here, $X = \hat{v}_w / \hat{v}_\infty$, where $\hat{v}_w$ is the undisturbed wind speed far upstream of the wind turbine, and $\hat{v}_\infty$ is the undisturbed wind speed far downstream of the wind turbine. This formula serves to derive the Betz-Joukowsky limit [98] [99] of

\[
C_p = 16/27 = 0.593
\]

that occurs at $X = 1/3$. This means that, in case of this limit, the wind turbine reduces the wind speed at hub height by one third. Assuming, for instance, $\hat{v}_w = 7.5$ m·s$^{-1}$ at hub height of $z = 80$ m would provide $\hat{v}_\infty = 2.5$ m·s$^{-1}$ at the same height. According to Equation (2.13) and a shear exponent of $p = 1/7$, such a decrease in wind speed at hub height would reduce the wind speed at the anemometer height, $z_R$, from nearly $\hat{v}_{w,R} = 5.6$ m·s$^{-1}$ far upstream of the wind turbine to about $\hat{v}_{w,R} = 1.9$ m·s$^{-1}$ far downstream of the wind turbine. The difference is $\Delta v_R = \hat{v}_{w,R} - \hat{v}_{w,R} = 3.7$ m·s$^{-1}$. A value of $C_p = 0.45$ which is realistic for horizontal winds speed at hub height ranging
from 5 m·s⁻¹ to 10 m·s⁻¹ (Figure 11) reduces \( \tilde{v}_w = 7.5 \text{ m·s}^{-1} \) at hub height of \( z = 80 \text{ m} \) to \( v_w = 5.1 \text{ m·s}^{-1} \). Using again \( p = 1/7 \), the wind speed \( \tilde{v}_w = 5.1 \text{ m·s}^{-1} \) provides \( \tilde{v}_{w,R} = 3.8 \text{ m·s}^{-1} \) and, hence, \( \Delta v_R = 1.8 \text{ m·s}^{-1} \). The decrease of near-surface wind speeds caused by wind turbines for numerous values of the power efficiency \( C_p \) given by Equation (3.20) and the three different shear exponents \( p = 1/10 \), \( p = 1/7 \) and \( p = 1/5 \) are listed in Table 4. Based on these results, a notable change of the local or regional climate—depending on the size of the wind farm—is to be expected. Note that these estimates presuppose that the thermal stratification and, hence, the shear exponents are unaffected by the wind turbines. However, we must expect the interaction between the wind field, wind turbine generating vortices, and enhancing turbulence in its wake may cause that thermal stratification tends to neutral conditions.

4. The Prediction of Wind Power

The wind power is predicted based on current state-of-the-art wind turbines of different rated powers listed in Table 2 [15] [34] [35]. We discretized the power curves published by the manufacturers when other data were not available. Figure 10 illustrates the power curves of these seven wind turbines. These power curves are based on standard conditions, i.e., air temperature of 15°C, air density of 1.225 kg·m⁻³, air pressure of 1013.25 hPa, and an undisturbed horizontal flow with a turbulence intensity ranging from 0.10 to 0.12. Figure 11 shows the corresponding power efficiencies.

Based on discrete power-curve data, we determined the empirical fitting parameters \( A, K, Q, B, S, \) and \( u \) of the general logistic function

\[
P(v) = A + \frac{K - A}{(1 + Q \exp\{-B(v - S)\})^u},
\]

(4.1)

where \( P(v) \) represents the power generated by the respective wind turbine at the wind speed \( v \) at hub height. The parameters obtained are listed in Table 5.

Table 4. The decrease of near-surface wind speed caused by wind turbines for numerous values of the power efficiency, \( C_p \), given by Equation (3.20) and the shear exponents, \( p \), used in this study. A horizontal wind speed of \( \tilde{v}_w = 7.5 \text{ m·s}^{-1} \) at hub height of \( z = 80 \text{ m} \) was assumed.

| \( X = \tilde{v}_w/\tilde{v}_e \) | \( C_p \) | \( \tilde{v}_{e,A} \text{ (m·s}^{-1}\) | \( \Delta v_e = \tilde{v}_{e,A} - \tilde{v}_e \text{ (m·s}^{-1}\) |
|---|---|---|---|
| 0.333 | 0.593 | 4.1 | 3.7 |
| 0.618 | 0.500 | 2.3 | 2.1 |
| 0.682 | 0.450 | 6.1 | 5.6 |
| 0.733 | 0.400 | 1.6 | 1.5 |
| 0.778 | 0.350 | 1.3 | 1.2 |
| 0.818 | 0.300 | 1.1 | 1.0 |
Figure 10. Power curves of the seven wind turbines listed in Table 2 (adopted from [19]).

Figure 11. Power efficiencies of the seven wind turbines listed in Table 2 (adopted from [19]).

Table 5. Parameters used in the generalized logistic function, Equation (4.1), to model the turbines' power curves. Values for Senvion MM92 and Mitsubishi MWT95/2.4 are from Ross et al. [34], the others are from Kramm et al. [19].

| Wind turbine         | A      | K      | Q      | B      | S      | u      |
|----------------------|--------|--------|--------|--------|--------|--------|
| Enercon E-48         | -24.9  | 811.2  | 0.54   | 1.0    | 10.9   | 2.3    |
| Suzlon S64 Mk II -1.25 MW | -56.5  | 1250.6 | 3.88   | 2.0    | 9.6    | 4.5    |
| General Electric 1.6-82.5 | -315.7 | 1601.3 | 1.66   | 2.0    | 9.8    | 7.2    |
| Senvion MM92         | -267.6 | 2050.4 | 19.5   | 1.9    | 8.5    | 6.2    |
| Mitsubishi MWT95/2.4 | -270.4 | 2403.3 | 12.2   | 1.5    | 8.8    | 4.9    |
| Enercon E-82 E4      | -113.8 | 3038.8 | 1.49   | 0.6    | 10.6   | 1.7    |
| Siemens SWT-3.6-107  | -414.3 | 3599.6 | 40.0   | 1.4    | 9.0    | 5.4    |
For each period, we calculated the average power output by

\[
\langle P_{WT} \rangle = \int_{v_i}^{v_o} f(v)P(v)dv.
\]  

(4.2)

Here, \( v_i \) is the cut-in wind speed, \( v_o \) is the cut-out wind speed, and \( f(v) \) is the probability density function of a given horizontal wind speed at hub height, \( v \), occurring during a period. It is expressed by the Weibull two-parameter distribution [100],

\[
f(v)dv = \frac{k_w}{c_w} \left( \frac{v}{c_w} \right)^{k_w-1} \exp \left( -\left( \frac{v}{c_w} \right)^{k_w} \right) dv,
\]  

(4.3)

where \( k_w \) and \( c_w \) represent the shape and scale parameters, respectively (e.g., [16] [70] [71]). The scale factor has units of speed and is closely related to the mean wind speed at hub height. The shape parameter is a non-dimensional quantity inversely related to the variance of the wind speed [101]. The integration of Equation (4.3) leads to the cumulative distribution function [100]

\[
F(v) = 1 - \exp \left( -\left( \frac{v}{c_w} \right)^{k_w} \right),
\]  

(4.4)

where \( F(v) \rightarrow 1 \) for \( v \rightarrow \infty \). The shape and scale parameters are determined for each of Alaska’s 19 first-order weather stations for Period I by fitting the histograms of the normalized cumulative frequency of the predicted wind speeds at the hub height \( z = 80 \text{ m} \) using the three different shear exponents, \( p = 1/10, \ p = 1/7 \) and \( p = 1/5 \). For Barrow, Big Delta, Kotzebue, Nome, Bethel, King Salmon, Juneau, Annette, St. Paul Island, Kodiak, and Cold Bay, \( k_w \) and \( c_w \) were also determined for Periods II and III. Figure 12 exemplarily

![Figure 12](image)

**Figure 12.** (a) Fitted normalized cumulative frequency and (b) probability density function of the predicted wind speeds at the hub height \( z = 80 \text{ m} \) as obtained for Cold Bay using a shear exponent of \( p = 1/7 \). The probabilities \( P_1, P_2, \) and \( P_3 \) that the daily mean wind speed will be in one of these colored areas are defined by Equations (4.5) to (4.7).
shows both the fitted normalized cumulative frequency for Period I and the corresponding Weibull distribution at hub height obtained for Cold Bay using \( p = 1/7 \). The results are listed in Table 6. Obviously, the scale parameters obtained for Periods II and III also indicate the near-surface wind-speed stilling, with exception of Barrow and Big Delta.

The probability that the daily mean wind speed does not meet the cut-in speed requirements of the different wind turbines considered in this study is given by

\[
P_1 = P[v_c] = F(v_c).
\]

Furthermore, the probability that the daily mean wind speed is in the range between \( v_c \) and the wind speed of the rated power, \( v_{pr} \), is given by

\[
P_2 = P[v_c, v_{pr}] = F(v_{pr}) - F(v_c).
\]

The probability that the daily mean wind speed exceeds \( v_{pr} \) results in

\[
P_3 = P[v_{pr}, v_{max}] = F(v_{max}) - F(v_{pr}),
\]

where \( F(v_{max}) \approx 1 \) for the maximum value \( v_{max} \) of the daily mean wind speed. For the purpose of simplification, a common cut-in wind speed of \( v_c = 3.0 \text{ m/s} \) and a common wind speed of the rated power of \( v_{pr} = 13.0 \text{ m/s} \) are assumed. Both wind speeds are averages derived from the wind turbine specifications (Table 2). The sum \( P_2 + P_3 \) broadly coincides with the operating range of a modern wind turbine.

The ratio of the average power output, \( P_{WT} \), provided by a wind turbine to its rated power, \( P_R \), is the capacity factor

\[
C_F = \frac{P_{WT}}{P_R}.
\]

The capacity factor may empirically be related to the ratio \( R_p = P_3/(P_2 + P_3) \).

5. Results

5.1. Hourly Mean Wind Speeds versus Daily Mean Wind Speeds

Because of Inequality (2.8), we must expect that hourly mean wind speeds provide higher wind-power outputs than daily mean wind speeds. To estimate possible deviations, we used (a) the hourly mean wind speeds and (b) daily mean wind speeds both related to the wind speed measurements at anemometer height \( z_r = 8 \text{ m (26 ft)} \) at Bethel performed from January 1, 1979 to December 31, 1983. Results obtained at \( z = 80 \text{ m} \) are illustrated in Figure 13 and Figure 14, where, again, \( p = 1/10 \), \( p = 1/7 \) and \( p = 1/5 \) were used.

Figure 13 shows the probability density functions of (a) the hourly mean wind speeds and (b) the daily mean wind speeds at the hub height. Obviously, these probability density functions remarkably differ so that—according to Equation (4.2)—different amounts of wind power were predicted for each of the seven wind turbines considered. Figure 14 shows the predicted wind power, \( \{P_{WT, A}\} \), obtained from the hourly mean wind speeds and the corresponding
Table 6. Weibull shape and scale parameters deduced from the predicted wind speeds at hub height of $z=80\,m$ for Alaska’s 19 first-order weather stations using three different shear exponents, $p = 1/10$, $p = 1/7$ and $p = 1/5$. Predicted wind speeds are based on the daily mean wind speeds at the respective anemometer heights for Periods I, II, and III.

| Location          | Period | Shape parameter $k_w$ | Scale parameter $c_w$ (m-s$^{-1}$) |
|-------------------|--------|-----------------------|-----------------------------------|
|                   |        | Shear exponent $p$    | 1/10 | 1/7 | 1/5 | 1/10 | 1/7 | 1/5 |
| Barrow WSO        | I      | 2.451                 | 2.458 | 2.460 | 7.568 | 8.362 | 9.554 |
|                   | II     | 2.683                 | 2.708 | 2.703 | 7.517 | 8.326 | 9.505 |
|                   | III    | 2.267                 | 2.269 | 2.272 | 7.444 | 8.237 | 9.409 |
| Bettles           | I      | 2.289                 | 2.306 | 2.270 | 3.373 | 3.686 | 4.151 |
|                   | II     | 1.707                 | 1.715 | 1.698 | 2.803 | 3.062 | 3.442 |
|                   | III    | 1.274                 | 1.280 | 1.212 | 5.178 | 5.657 | 6.154 |
| Big Delta FAA/AMOS| II     | 1.141                 | 1.140 | 1.154 | 4.892 | 5.206 | 6.026 |
|                   | III    | 1.349                 | 1.338 | 1.346 | 5.229 | 5.830 | 6.450 |
| McGrath           | I      | 1.702                 | 1.711 | 1.694 | 2.902 | 3.170 | 3.566 |
|                   | II     | 1.190                 | 1.188 | 1.185 | 3.385 | 3.681 | 4.149 |
|                   | III    | 1.868                 | 1.889 | 1.889 | 6.994 | 7.763 | 8.865 |
| Gulkana           | I      | 2.094                 | 2.102 | 2.100 | 7.591 | 8.400 | 9.594 |
|                   | II     | 1.688                 | 1.692 | 1.693 | 6.397 | 7.083 | 8.091 |
|                   | III    | 1.873                 | 1.880 | 1.879 | 5.753 | 6.374 | 7.279 |
| Kotzebue WSO      | I      | 1.693                 | 1.700 | 1.701 | 5.393 | 5.972 | 6.825 |
|                   | II     | 1.693                 | 1.700 | 1.701 | 5.393 | 5.972 | 6.825 |
|                   | III    | 1.710                 | 1.716 | 1.722 | 2.757 | 3.062 | 3.502 |
| Nome WSO          | I      | 2.132                 | 2.063 | 2.076 | 5.938 | 6.504 | 7.438 |
|                   | II     | 1.693                 | 1.700 | 1.701 | 5.393 | 5.972 | 6.825 |
|                   | III    | 1.873                 | 1.880 | 1.879 | 5.753 | 6.374 | 7.279 |
| Bethel            | I      | 2.714                 | 2.718 | 2.561 | 7.520 | 8.312 | 9.371 |
|                   | II     | 2.290                 | 2.276 | 2.294 | 6.719 | 7.423 | 8.495 |
|                   | III    | 1.710                 | 1.716 | 1.722 | 2.757 | 3.062 | 3.502 |
| Talkeetna         | I      | 2.247                 | 2.248 | 2.257 | 4.213 | 4.669 | 5.334 |
| Anchorage INTL    | I      | 2.295                 | 2.306 | 2.315 | 4.146 | 4.596 | 5.253 |
| Homer             | I      | 2.271                 | 2.276 | 2.277 | 5.685 | 6.223 | 7.016 |
|                   | II     | 2.675                 | 2.805 | 2.686 | 6.276 | 6.968 | 7.741 |
| King Salmon       | I      | 2.031                 | 2.065 | 2.041 | 5.369 | 5.903 | 6.637 |
|                   | II     | 1.733                 | 1.741 | 1.725 | 3.394 | 3.706 | 4.176 |
| Yakutat           | I      | 1.556                 | 1.554 | 1.552 | 4.458 | 4.862 | 5.491 |
| Juneau            | I      | 1.700                 | 1.693 | 1.721 | 4.760 | 5.195 | 5.887 |
|                   | II     | 1.424                 | 1.424 | 1.421 | 4.097 | 4.465 | 5.049 |
|                   | III    | 1.797                 | 1.783 | 1.795 | 4.657 | 5.069 | 5.743 |
| Annette WSO       | I      | 2.052                 | 2.050 | 2.114 | 5.183 | 5.663 | 6.468 |
|                   | II     | 1.624                 | 1.624 | 1.618 | 4.056 | 4.421 | 4.995 |
Continued

| Location     | I  | II   | III  |
|--------------|----|------|------|
| St. Paul Island | 2.449 | 2.610 | 1.998 |
|           | 2.450 | 2.593 | 2.386 |
|           | 2.462 | 2.610 | 2.278 |
|           | 9.235 | 9.400 | 2.113 |
|           | 10.103 | 10.273 | 2.055 |
|           | 11.396 | 11.587 | 2.058 |
| Kodiak     | 2.468 | 2.610 | 2.278 |
|           | 2.470 | 2.593 | 2.287 |
|           | 9.235 | 9.400 | 6.306 |
|           | 10.103 | 10.273 | 6.959 |
|           | 11.396 | 11.587 | 7.777 |
| Cold Bay  | 2.468 | 2.610 | 2.278 |
|           | 2.470 | 2.593 | 2.287 |
|           | 9.235 | 9.400 | 8.989 |
|           | 10.103 | 10.273 | 9.839 |
|           | 11.396 | 11.587 | 11.093 |

Figure 13. Probability density functions at hub height of $z = 80$ m derived from (a) hourly mean wind speeds and (b) daily mean wind speeds both using wind speed measurements performed at the anemometer height $z_a = 8$ m (26 ft) in Bethel during January 1, 1979 to December 31, 1983 for $p = 1/10$, $p = 1/7$ and $p = 1/5$.

capacity factor, $C_{F,h}$. As expected, we obtained for $p = 1/5$ (stable stratification) always the highest values of $\langle P_{WT,h} \rangle$ and $C_{F,h}$ for each wind turbine, followed by those for $p = 1/7$ (neutral stratification) and $p = 1/10$ (unstable stratification). The General Electric 1.6 - 82.5 and Senvion MM92 have the highest and second highest capacity factor, respectively. This result agrees with that of Mölders et al. [15].

Figure 14 shows the relative differences between $\langle P_{WT,h} \rangle$ and that based on the daily mean wind speeds, $\langle P_{WT,d} \rangle$, expressed by

$$\Delta P_{WT,h} = \frac{\langle P_{WT,h} \rangle - \langle P_{WT,d} \rangle}{\langle P_{WT,h} \rangle}.$$  \hspace{1cm} (5.1)

For $p = 1/10$ this relative difference is always positive, i.e., the predicted wind power based on hourly mean wind speeds always exceeds that calculated with daily mean wind speeds. For the shear exponents $p = 1/7$ and $p = 1/5$,
Figure 14. As in Figure 13, but for (a) the predicted wind power, $P_{WT,a}$, (b) the corresponding capacity factor, $C_{F,a}$, and (c) relative difference $\Delta P_{WT,a}$ as expressed by Equation (5.1).

however, positive as well as negative values of $\Delta P_{WT}$ occur. Negative values can be attributed to the fitted curves of the normalized frequencies in case of the daily mean wind speeds. In contrast to the case of the hourly mean wind speeds, these fitted curves slightly overestimated the normalized frequencies in the range from 9 m∙s$^{-1}$ to 15 m∙s$^{-1}$. Thus, we must expect that for the same period, hourly mean wind speeds provide slightly higher average wind-power outputs, $\langle P_{WT,a} \rangle$, than daily mean wind speeds, $\langle P_{WT,d} \rangle$.

5.2. Daily Mean Wind Speeds

Our predicted wind power obtained for Barrow, Big Delta, Kotzebue, Nome, Bethel, King Salmon, Juneau, St. Paul Island, Kodiak, and Cold Bay for Periods I, II, and III using $\ p = 1/10$, $\ p = 1/7$ and $\ p = 1/5$, is listed in Table 7. The effect of the shear exponent on the probability density function and the wind-power output predicted for Periods I, II, and III is exemplarily shown in Figure 15 to Figure 17 for Cold Bay.

Figure 15 and Figure 16 show the results obtained for the seven wind turbines of different rated power (see Table 2). Generally, the power output predicted at
Table 7. Wind power predicted for first-order weather stations Barrow, Big Delta, Kotzebue, Nome, Bethel, King Salmon, Juneau, Annette, St. Paul Island, Kodiak, and Cold Bay and Periods I, II, and III using \( p = 1/10 \), \( p = 1/7 \) and \( p = 1/5 \).

| Weather station     | \( p \) | Period | Wind turbine |
|---------------------|--------|--------|-------------|
|                     |        |        | E-48 (kW)  | S64 Mk II-1.25 kW | GE 1.6-8.25 kW | MM92 (kW) | MW95/2.4 (kW) | E-82E4 (kW) | SWT-3.6-107 (kW) |
| Barrow WSO          | 1/10   | I      | 230        | 360        | 584        | 731        | 766        | 672        | 977        |
|                     |        | II     | 222        | 346        | 574        | 717        | 745        | 643        | 940        |
|                     |        | III    | 225        | 352        | 566        | 710        | 746        | 662        | 958        |
|                     | 1/7    | I      | 287        | 456        | 707        | 887        | 943        | 848        | 1221       |
|                     |        | II     | 282        | 450        | 708        | 887        | 937        | 826        | 1199       |
|                     |        | III    | 279        | 443        | 683        | 858        | 915        | 833        | 1192       |
|                     | 1/5    | I      | 367        | 589        | 869        | 1094       | 1188       | 1117       | 1575       |
|                     |        | II     | 368        | 592        | 881        | 1108       | 1197       | 1104       | 1573       |
|                     |        | III    | 355        | 567        | 836        | 1054       | 1145       | 1087       | 1525       |
| Big Delta FAA/AMOS  | 1/10   | I      | 138        | 211        | 333        | 421        | 448        | 422        | 592        |
|                     |        | II     | 135        | 207        | 321        | 406        | 436        | 418        | 581        |
|                     |        | III    | 135        | 205        | 328        | 414        | 438        | 409        | 577        |
|                     | 1/7    | I      | 162        | 250        | 387        | 488        | 524        | 500        | 697        |
|                     |        | II     | 151        | 232        | 355        | 448        | 484        | 468        | 648        |
|                     |        | III    | 167        | 258        | 400        | 505        | 541        | 514        | 718        |
|                     | 1/5    | I      | 191        | 296        | 445        | 560        | 610        | 597        | 821        |
|                     |        | II     | 187        | 291        | 435        | 548        | 598        | 590        | 808        |
|                     |        | III    | 199        | 309        | 468        | 590        | 639        | 616        | 855        |
| Kotzebue WSO        | 1/10   | I      | 207        | 322        | 510        | 642        | 680        | 619        | 885        |
|                     |        | II     | 239        | 375        | 589        | 740        | 785        | 711        | 1019       |
|                     |        | III    | 178        | 275        | 439        | 553        | 585        | 535        | 763        |
|                     | 1/7    | I      | 254        | 400        | 612        | 771        | 827        | 770        | 1089       |
|                     |        | II     | 291        | 461        | 700        | 881        | 947        | 880        | 1247       |
|                     |        | III    | 219        | 341        | 528        | 665        | 711        | 664        | 938        |
|                     | 1/5    | I      | 318        | 504        | 744        | 938        | 1022       | 986        | 1371       |
|                     |        | II     | 363        | 577        | 842        | 1062       | 1161       | 1125       | 1562       |
|                     |        | III    | 276        | 434        | 647        | 816        | 886        | 854        | 1186       |
| Nome WSO            | 1/10   | I      | 130        | 194        | 335        | 422        | 435        | 385        | 557        |
|                     |        | II     | 130        | 192        | 340        | 428        | 437        | 382        | 555        |
|                     |        | III    | 119        | 178        | 304        | 383        | 396        | 355        | 510        |
|                     | 1/7    | I      | 168        | 257        | 423        | 532        | 556        | 497        | 716        |
|                     |        | II     | 168        | 257        | 430        | 540        | 561        | 495        | 717        |
|                     |        | III    | 152        | 232        | 381        | 480        | 503        | 455        | 651        |
Continued

| City        | Date | I | II | III | I  | II  | III |
|-------------|------|---|----|-----|----|-----|-----|
| Bethel      | 1/10 | 189 | 221 | 175 | 242 | 281 | 223 |
|             |      | 220 | 222 | 266 | 280 | 248 | 349 |
|             | 1/7  | 290 | 345 | 266 | 611 | 706 | 563 |
|             |      | 293 | 375 | 452 | 765 | 884 | 706 |
|             | 1/5  | 490 | 574 | 567 | 634 | 575 | 530 |
| King Salmon | 1/10 | 110 | 134 | 101 | 142 | 179 | 131 |
|             |      | 157 | 195 | 144 | 212 | 271 | 193 |
|             | 1/7  | 293 | 375 | 452 | 364 | 530 | 340 |
|             |      | 368 | 470 | 476 | 706 | 428 | 438 |
|             | 1/5  | 368 | 375 | 452 | 884 | 933 | 823 |
| Juneau      | 1/10 | 79  | 85  | 71  | 100 | 109 | 89  |
|             |      | 112 | 121 | 101 | 146 | 160 | 130 |
|             | 1/7  | 202 | 220 | 179 | 252 | 277 | 223 |
|             |      | 256 | 279 | 228 | 319 | 350 | 283 |
|             | 1/5  | 202 | 279 | 228 | 319 | 350 | 283 |
| Annette WSO | 1/10 | 75  | 91  | 57  | 97  | 117 | 73  |
|             |      | 104 | 126 | 76  | 139 | 171 | 102 |
|             | 1/7  | 195 | 239 | 146 | 250 | 306 | 218 |
|             |      | 248 | 304 | 187 | 316 | 386 | 239 |
|             | 1/5  | 248 | 304 | 187 | 316 | 386 | 239 |

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Continued

| Weather Station | Column 1 | Column 2 | Column 3 | Column 4 | Column 5 | Column 6 | Column 7 |
|-----------------|----------|----------|----------|----------|----------|----------|----------|
| St. Paul Island | III 102  | 150      | 261      | 329      | 339      | 304      | 437      |
|                 | I 347    | 555      | 828      | 1042     | 1125     | 1046     | 1483     |
|                 | II 360   | 577      | 861      | 1083     | 1169     | 1081     | 1537     |
|                 | III 329  | 524      | 785      | 988      | 1067     | 996      | 1409     |
|                 | 1/7 I 401| 643      | 933      | 1176     | 1287     | 1236     | 1725     |
|                 | II 416   | 668      | 966      | 1219     | 1334     | 1277     | 1786     |
|                 | III 381  | 609      | 886      | 1118     | 1222     | 1176     | 1639     |
|                 | 1/5 I 472| 755      | 1062     | 1342     | 1491     | 1495     | 2041     |
|                 | II 489   | 783      | 1098     | 1389     | 1544     | 1548     | 2115     |
|                 | III 448  | 715      | 1071     | 1176     | 1417     | 1420     | 1938     |
| Kodiak          | 1/10 I 156| 236      | 401      | 504      | 521      | 459      | 665      |
|                 | II 191   | 294      | 494      | 619      | 641      | 558      | 813      |
|                 | III 130  | 193      | 334      | 421      | 433      | 383      | 554      |
|                 | 1/7 I 196| 304      | 496      | 623      | 652      | 579      | 837      |
|                 | II 237   | 373      | 598      | 750      | 788      | 697      | 1010     |
|                 | III 163  | 248      | 411      | 517      | 539      | 481      | 693      |
|                 | 1/5 I 252| 396      | 615      | 774      | 824      | 754      | 1076     |
|                 | II 306   | 487      | 744      | 934      | 1000     | 914      | 1306     |
|                 | III 217  | 339      | 534      | 672      | 713      | 650      | 928      |
| Cold Bay        | 1/10 I 379| 608      | 894      | 1126     | 1224     | 1154     | 1626     |
|                 | II 409   | 659      | 959      | 1209     | 1318     | 1246     | 1754     |
|                 | III 349  | 558      | 828      | 1043     | 1129     | 1060     | 1496     |
|                 | 1/7 I 434| 697      | 997      | 1258     | 1385     | 1351     | 1872     |
|                 | II 466   | 749      | 1063     | 1343     | 1483     | 1435     | 2010     |
|                 | III 402  | 644      | 930      | 1174     | 1287     | 1246     | 1731     |
|                 | 1/5 I 502| 802      | 1116     | 1411     | 1577     | 1608     | 2176     |
|                 | II 535   | 855      | 1181     | 1494     | 1675     | 1721     | 2321     |
|                 | III 469  | 749      | 1052     | 1329     | 1480     | 1494     | 2031     |

Hub height for each of these weather stations non-linearly depends on the shear exponent of the power law (see Equation (2.13)). For $p = 1/10$, each wind turbine provides the lowest wind-power output. Whereas the opposite is true in case of $p = 1/5$. Consequently, the capacity factor for each wind turbine is the lowest for $p = 1/10$ and the highest for $p = 1/5$ (see Table 8).

Based on the capacity factors for Period I, Cold Bay, St. Paul Island, Barrow, Bethel, and Kotzebue would be very good candidates for wind farms, as already found by Cooney and Kramm [105] for a short period, but Cold Bay and St. Paul Island changed their ranks. At Kodiak, Nome, King Salmon, and Big Delta, wind-power generation may be considered for the reduction of fossil fuel consumption. In
Figure 15. Probability density functions at the hub height of $z = 80 \text{ m}$ for (a) Period I, (b) Period II, and (c) Period III determined for Cold Bay from the daily mean wind speeds related to the wind-speed measurements performed at the anemometer height $z_a = 10 \text{ m (33 ft)}$ using $p = 1/10$, $p = 1/7$ and $p = 1/5$. 
Figure 16. Predicted wind-power output $\left\langle P_{\text{turb}} \right\rangle$ at hub height $z = 80 \text{ m}$ for Cold Bay using seven wind turbines of different rated power (Table 2) as well as $p = 1/10$, $p = 1/7$, and $p = 1/5$.

Figure 17. As in Figure 16, but for the predicted capacity factor $C_{\text{turb}}$.
Table 8. As in Table 7, but for the capacity factor.

| Weather station | Period | Wind turbine | E-48 (%) | S64 Mk II-1.25 MW (%) | GE 1.6-82.5 (%) | MM92 (%) | MWT95/2.4 (%) | E-82E4 (%) | SWT-3.6-107 (%) |
|------------------|--------|-------------|----------|-----------------------|----------------|----------|---------------|------------|-----------------|
| Barrow WSO       | 1/10   | I           | 28.4     | 28.8                  | 36.5           | 35.7     | 31.9          | 22.3       | 27.1            |
|                  |        | II          | 27.4     | 27.6                  | 35.9           | 35.0     | 31.0          | 21.3       | 26.1            |
|                  |        | III         | 27.8     | 28.1                  | 35.4           | 34.6     | 31.1          | 21.9       | 26.6            |
|                  | 1/7    | I           | 35.4     | 36.4                  | 44.2           | 43.3     | 39.3          | 28.1       | 33.9            |
|                  |        | II          | 34.9     | 36.0                  | 44.3           | 43.3     | 39.0          | 27.4       | 33.3            |
|                  |        | III         | 34.5     | 35.4                  | 42.7           | 41.9     | 38.1          | 27.6       | 33.1            |
|                  | 1/5    | I           | 45.4     | 47.1                  | 54.3           | 53.4     | 49.5          | 37.0       | 43.8            |
|                  |        | II          | 45.4     | 47.4                  | 55.1           | 54.1     | 49.9          | 36.6       | 43.7            |
|                  |        | III         | 43.8     | 45.4                  | 52.3           | 51.4     | 47.7          | 36.0       | 42.4            |
| Big Delta FAA/AMOS| 1/10  | I           | 17.0     | 16.9                  | 20.8           | 20.5     | 18.7          | 14.0       | 16.5            |
|                  |        | II          | 16.7     | 16.6                  | 20.1           | 19.8     | 18.2          | 13.8       | 16.1            |
|                  |        | III         | 16.6     | 16.4                  | 20.5           | 20.2     | 18.3          | 13.5       | 16.0            |
|                  | 1/7    | I           | 20.0     | 20.0                  | 24.2           | 23.8     | 21.8          | 16.6       | 19.4            |
|                  |        | II          | 18.6     | 18.5                  | 22.2           | 21.9     | 20.1          | 15.5       | 18.0            |
|                  |        | III         | 20.6     | 20.6                  | 25.0           | 24.6     | 22.5          | 17.0       | 20.0            |
|                  | 1/5    | I           | 23.5     | 23.7                  | 27.8           | 27.3     | 25.4          | 19.8       | 22.8            |
|                  |        | II          | 23.1     | 23.3                  | 27.2           | 26.7     | 24.9          | 19.5       | 22.5            |
|                  |        | III         | 24.5     | 24.7                  | 29.3           | 28.8     | 26.6          | 20.4       | 23.7            |
| Kotzebue WSO     | 1/10   | I           | 25.5     | 25.7                  | 31.9           | 31.3     | 28.3          | 20.5       | 24.6            |
|                  |        | II          | 29.5     | 30.0                  | 36.8           | 36.1     | 32.7          | 23.5       | 28.3            |
|                  |        | III         | 22.0     | 22.0                  | 27.5           | 27.0     | 24.4          | 17.7       | 21.2            |
|                  | 1/7    | I           | 31.4     | 32.0                  | 38.3           | 37.6     | 34.4          | 25.5       | 30.2            |
|                  |        | II          | 35.9     | 36.9                  | 43.7           | 43.0     | 39.5          | 29.2       | 34.6            |
|                  |        | III         | 27.0     | 27.3                  | 33.0           | 32.4     | 29.6          | 22.0       | 26.0            |
|                  | 1/5    | I           | 39.3     | 40.3                  | 46.5           | 45.8     | 42.6          | 32.7       | 38.1            |
|                  |        | II          | 44.8     | 46.2                  | 52.6           | 51.8     | 48.4          | 37.3       | 43.4            |
|                  |        | III         | 34.0     | 34.7                  | 40.5           | 39.8     | 36.9          | 28.3       | 33.0            |
| Nome WSO         | 1/10   | I           | 16.1     | 15.5                  | 20.9           | 20.6     | 18.1          | 12.8       | 15.5            |
|                  |        | II          | 16.1     | 15.3                  | 21.3           | 20.9     | 18.2          | 12.7       | 15.4            |
|                  |        | III         | 14.7     | 14.2                  | 19.0           | 18.7     | 16.5          | 11.7       | 14.2            |
|                  | 1/7    | I           | 20.7     | 20.5                  | 26.4           | 25.9     | 23.2          | 16.5       | 19.9            |
|                  |        | II          | 20.8     | 20.5                  | 26.9           | 26.4     | 23.4          | 16.4       | 19.9            |
|                  |        | III         | 18.8     | 18.6                  | 23.8           | 23.4     | 21.0          | 15.1       | 18.1            |
|                  | 1/5    | I           | 27.7     | 28.0                  | 34.3           | 33.7     | 30.6          | 22.3       | 26.7            |
| Location       | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 |
|----------------|--------|--------|--------|--------|--------|
| Bethel 1/10    | 23.3   | 27.3   | 21.5   | 29.9   | 36.6   |
|                | 23.2   | 27.6   | 21.3   | 30.4   | 37.7   |
|                | 30.6   | 35.9   | 28.3   | 35.2   | 45.0   |
|                | 29.9   | 35.0   | 27.6   | 34.4   | 44.1   |
|                | 26.4   | 31.0   | 24.4   | 30.9   | 43.1   |
|                | 18.2   | 21.3   | 16.9   | 23.5   | 38.9   |
|                | 22.3   | 26.1   | 20.6   | 25.3   | 33.2   |
| King Salmon 1/10 | 13.6   | 17.6   | 22.1   | 16.1   | 36.6   |
|                | 12.5   | 16.9   | 21.7   | 15.5   | 37.7   |
|                | 18.3   | 23.4   | 29.8   | 21.3   | 45.0   |
|                | 18.0   | 22.9   | 29.0   | 20.9   | 44.1   |
|                | 15.5   | 20.0   | 25.3   | 18.3   | 40.4   |
|                | 10.8   | 13.8   | 17.2   | 12.7   | 29.4   |
| Juneau 1/10    | 9.7    | 17.6   | 22.1   | 16.1   | 21.9   |
|                | 9.0    | 16.9   | 21.7   | 15.5   | 28.2   |
|                | 12.6   | 23.4   | 29.8   | 21.3   | 27.7   |
|                | 12.5   | 22.9   | 29.0   | 20.9   | 44.1   |
|                | 10.9   | 20.0   | 25.3   | 18.3   | 40.4   |
|                | 7.8    | 13.8   | 17.2   | 12.7   | 29.4   |
| Annette WSO 1/10 | 9.3    | 12.3   | 21.9   | 16.1   | 9.0    |
|                | 8.3    | 11.7   | 21.7   | 15.5   | 21.8   |
|                | 12.2   | 15.8   | 29.8   | 21.3   | 28.2   |
|                | 12.1   | 15.6   | 29.0   | 20.9   | 44.1   |
|                | 10.4   | 13.7   | 25.3   | 18.3   | 40.4   |
|                | 7.4    | 9.8    | 17.2   | 12.7   | 29.4   |
Rural Alaska, fossil fuel is particularly expensive; wind power may contribute to holding costs affordable. The generation of wind power at Barrow would strongly be limited by the operating temperature range unless cold climate versions of wind turbines like Senvion’s MM92 CCV with limits of −30°C and lower would be deployed. At Annette and Juneau wind power is generally ineffective.

The typical distribution of the capacity factor is illustrated in Figure 17. Again, the General Electric 1.6 - 82.5 and Senvion MM92 have the highest and second highest capacity factor, respectively [15]. Nonetheless, capacity factors of more than 50% for \( p = 1/7 \) and more than 60% for \( p = 1/5 \) as obtained in Period I for most of these wind turbines in case of Cold Bay are extraordinary.

Figure 18 shows the relative decrease.
Figure 18. Relative decrease of predicted wind power at first-order weather stations (a) Barrow, (b) Big Delta, (c) Kotzebue, (d) Nome, (e) Bethel, (f) King Salmon, (g) Juneau, (h) Annette, (i) St. Paul Island, (j) Kodiak, and (k) Cold Bay for the seven wind turbines of different rated power (Table 2) as well as $p = 1/10$, $p = 1/7$, and $p = 1/5$.

$$
\Delta P_{WT,I} = \frac{\langle P_{WT.I} \rangle - \langle P_{WT.III} \rangle}{\langle P_{WT.I} \rangle},
$$

at each of the weather stations, where $\langle P_{WT.I} \rangle$ is the average wind power predicted for Period II and $\langle P_{WT.III} \rangle$ is that predicted for Period III. Besides Big Delta that suggests a relative increase in wind power of up to 12% for $p = 1/7$, we found notable relative decreases in the predicted wind power of about 38% for Annette, followed by Kodiak ($=30\%$), King Salmon ($=26\%$), and Kotzebue ($=24\%$), where the effect of the shear exponents was marginal in these instances. Bethel with about 17% for $p = 1/5$ and about 20% for $p = 1/10$ and $p = 1/7$, Juneau with about 18% hardly affected by the shear exponents, and Cold Bay with about 14% for $p = 1/10$ to 10% for $p = 1/5$ also show remarkable relative decreases in predicted wind power. In case of Nome, the relative decrease in the predicted wind power is less than 12%. However, the results notably depend on both the chosen wind turbine and the shear exponent. St. Paul Island exhibits a small relative decrease of about 8% hardly affected by the shear exponents. Barrow shows a relative increase mainly for $p = 1/7$ and $p = 1/5$, but this in-
crease is less than 5%.

In case of Annette, predicted wind power dramatically decreased due to the near-surface wind-speed stilling from Period II to Period III, but with respect to Period I, wind-power generation at Annette is generally ineffective. The same is true for Juneau despite the relative decrease in the predicted wind power is twice as small as compared with Annette. At Cold Bay, Bethel and Kotzebue, which were very good candidates for wind farms based on Period I, the near-surface wind-speed stilling notably shrinks wind-power generation. The same is true in the case of Kodiak and King Salmon.

For the purpose of simplification, the probabilities $P_1$, $P_2$, and $P_3$ given by Equations (4.5) to (4.7) were computed for Periods I, II, and III using a common cut-in wind speed of $v_{ci} = 3.0 \text{ m} \cdot \text{s}^{-1}$ and a common wind speed of the rated power of $v_{pr} = 13.0 \text{ m} \cdot \text{s}^{-1}$. The results are listed in Table 9.

6. Discussion and Conclusions

Based on wind-speed record of its 19 first-order weather stations, we analyze the near-surface wind-speed stilling in the State of Alaska, USA during the period reaching from January 1, 1984 to December 31, 2016 denoted as Period I. With exception of Big Delta that indicates an increase of 0.0157 m∙s⁻¹∙a⁻¹, on average, all other first-order weather stations indicate declining trends in the near-surface wind speeds. In most cases, the average trends are less than −0.0300 m∙s⁻¹∙a⁻¹, with exception of Gulkana that only exhibits a value of −0.0043 m∙s⁻¹∙a⁻¹. The strongest trend was found at Homer with −0.0500 m∙s⁻¹∙a⁻¹, followed by Bettles with −0.0492 m∙s⁻¹∙a⁻¹ and Yakutat with −0.0453 m∙s⁻¹∙a⁻¹. At Barrow, the declining trend is marginal.

With respect to the National Renewable Energy Laboratory and the Alaska Energy Authority, the mean wind speed and the mean wind-power density computed for the Period I served to determine the wind-power class for each first-order weather station. This study finds Bettles, Fairbanks, McGrath, Gulkana, Talkeetna, Anchorage, Homer, and Yakutat are related to wind-power class 1, termed as “poor”. These stations are impractical options for wind farms because they are unable to meet the basic criteria. The wind speeds at these locations would not be high enough to sufficiently supply power to the surrounding cities and communities, respectively. Also, they would experience a lot of days without receiving any power because the wind speed was not high enough to overcome the turbines cut-in wind speed. Thus, even though they indicate remarkable declining trends in the near-surface wind speeds, these first-order weather stations were not further considered in our prediction of wind power.

This wind-power potential, however, is of subordinate importance because wind turbines only extract a fraction of the kinetic energy from the wind field as characterized by the power efficiency. Since the wind turbine technology has notably improved during the past 35 years, we hypothetically used seven currently available wind turbines of different rated power (Enercon E-48, Suzlon
Table 9. Predicted probabilities $P_1$, $P_2$, and $P_3$ based on Equations (4.5) to (4.7) for first-order weather stations Barrow, Big Delta, Kotzebue, Nome, Bethel, King Salmon, Juneau, Annette, St. Paul Island, Kodiak, and Cold Bay and Periods I, II, and III using $p = 1/10$, $p = 1/7$ and $p = 1/5$.

| Weather station | $p$ | Period | $P_1$ | $P_2$ | $P_3$ |
|-----------------|-----|--------|-------|-------|-------|
| Barrow WSO      | 1/10| I      | 0.098 | 0.879 | 0.023 |
|                 |     | II     | 0.082 | 0.906 | 0.013 |
|                 |     | III    | 0.120 | 0.851 | 0.029 |
|                 | 1/7 | I      | 0.077 | 0.871 | 0.052 |
|                 |     | II     | 0.061 | 0.904 | 0.035 |
|                 |     | III    | 0.096 | 0.844 | 0.060 |
|                 | 1/5 | I      | 0.056 | 0.825 | 0.118 |
|                 |     | II     | 0.043 | 0.860 | 0.097 |
|                 |     | III    | 0.072 | 0.804 | 0.124 |
| Big Delta FAA/AMOS | 1/10 | I   | 0.393 | 0.568 | 0.040 |
|                  |     | II    | 0.436 | 0.517 | 0.047 |
|                  |     | III   | 0.377 | 0.590 | 0.033 |
|                  | 1/7 | I     | 0.358 | 0.587 | 0.055 |
|                  |     | II    | 0.413 | 0.528 | 0.059 |
|                  |     | III   | 0.337 | 0.609 | 0.054 |
|                  | 1/5 | I     | 0.342 | 0.574 | 0.084 |
|                  |     | II    | 0.361 | 0.551 | 0.088 |
|                  |     | III   | 0.300 | 0.623 | 0.077 |
| Kotzebue WSO    | 1/10| I     | 0.186 | 0.773 | 0.041 |
|                 |     | II    | 0.133 | 0.821 | 0.046 |
|                 |     | III   | 0.243 | 0.720 | 0.037 |
|                 | 1/7 | I     | 0.153 | 0.776 | 0.071 |
|                 |     | II    | 0.108 | 0.810 | 0.082 |
|                 |     | III   | 0.208 | 0.730 | 0.061 |
|                 | 1/5 | I     | 0.121 | 0.751 | 0.127 |
|                 |     | II    | 0.083 | 0.766 | 0.151 |
|                 |     | III   | 0.170 | 0.723 | 0.107 |
| Nome WSO        | 1/10| I     | 0.256 | 0.734 | 0.010 |
|                 |     | II    | 0.208 | 0.787 | 0.005 |
|                 |     | III   | 0.310 | 0.679 | 0.012 |
|                 | 1/7 | I     | 0.215 | 0.763 | 0.022 |
|                 |     | II    | 0.183 | 0.801 | 0.015 |
|                 |     | III   | 0.267 | 0.710 | 0.023 |
|                 | 1/5 | I     | 0.172 | 0.777 | 0.051 |
| Location          | 1/10     | 1/7      | 1/5      |
|-------------------|----------|----------|----------|
| Bethel            |          |          |          |
| I                 | 0.119    | 0.093    | 0.069    |
| II                | 0.079    | 0.061    | 0.053    |
| III               | 0.146    | 0.119    | 0.088    |
| King Salmon       |          |          |          |
| I                 | 0.209    | 0.173    | 0.135    |
| II                | 0.130    | 0.090    | 0.075    |
| III               | 0.264    | 0.219    | 0.180    |
| Juneau            |          |          |          |
| I                 | 0.417    | 0.376    | 0.324    |
| II                | 0.366    | 0.326    | 0.269    |
| III               | 0.474    | 0.433    | 0.380    |
| Annette WSO       |          |          |          |
| I                 | 0.365    | 0.325    | 0.268    |
| II                | 0.278    | 0.238    | 0.179    |
| III               | 0.458    | 0.413    |          |
Continued

|                | III  | 0.355 | 0.636 | 0.009 |
|----------------|------|-------|-------|-------|
| St. Paul Island| 1/10 | 1     | 0.062 | 0.839 | 0.099 |
|                |      | II    | 0.049 | 0.853 | 0.097 |
|                |      | III   | 0.079 | 0.823 | 0.098 |
|                | 1/7  | I     | 0.050 | 0.794 | 0.157 |
|                |      | II    | 0.040 | 0.801 | 0.159 |
|                |      | III   | 0.065 | 0.784 | 0.152 |
|                | 1/5  | I     | 0.037 | 0.712 | 0.251 |
|                |      | II    | 0.029 | 0.712 | 0.259 |
|                |      | III   | 0.049 | 0.713 | 0.238 |
| Kodiak         | 1/10 | I     | 0.195 | 0.793 | 0.012 |
|                |      | II    | 0.124 | 0.864 | 0.013 |
|                |      | III   | 0.251 | 0.739 | 0.009 |
|                | 1/7  | I     | 0.155 | 0.821 | 0.024 |
|                |      | II    | 0.102 | 0.868 | 0.030 |
|                |      | III   | 0.216 | 0.764 | 0.019 |
|                | 1/5  | I     | 0.131 | 0.812 | 0.056 |
|                |      | II    | 0.077 | 0.853 | 0.070 |
|                |      | III   | 0.173 | 0.782 | 0.045 |
| Cold Bay       | 1/10 | I     | 0.051 | 0.823 | 0.126 |
|                |      | II    | 0.037 | 0.824 | 0.140 |
|                |      | III   | 0.067 | 0.823 | 0.110 |
|                | 1/7  | I     | 0.041 | 0.768 | 0.191 |
|                |      | II    | 0.029 | 0.758 | 0.213 |
|                |      | III   | 0.055 | 0.778 | 0.167 |
|                | 1/5  | I     | 0.030 | 0.676 | 0.294 |
|                |      | II    | 0.021 | 0.652 | 0.327 |
|                |      | III   | 0.041 | 0.699 | 0.260 |

S64 Mark II-1.25 MW, General Electric 1.6 - 82.5, Senvion MM92, Mitsubishi MWT95/2.4, Enercon E-82 E4, and Siemens SWT-3.6-107) and three different shear exponents to assess the wind-power sustainability under changing wind regimes. These machines were chosen because of an increase in rated power by an increment of about 400 kW. The three shear exponents $p = 1/10$, $p = 1/7$, and $p = 1/5$ were considered to cover the range of wind power for various conditions of thermal stratification.

Based on the capacity factors for Period I, Cold Bay, St. Paul Island, Barrow, Kotzebue, and Bethel would be very good candidates for wind farms. Kodiak, Nome, King Salmon, and Big Delta may be considered for specific reasons like...
the reduction of fossil fuel consumption which always plays a notable role in Rural Alaska. However, wind-power generation at Cold Bay, Bethel and Kotzebue is notably affected by this near-surface wind-speed stilling. The same is true in case of Kodiak and King Salmon, where the impact of this wind-speed stilling currently prevents sustainability of wind power at these two communities. As mentioned before, wind-power generation at Annette and Juneau is generally ineffective.

Cold Bay located in the Aleutians East Borough is an ideal site for a wind farm. It has a very high wind-power potential expressed by the wind-power class of 6, termed as “outstanding”. As illustrated in Figure 15, the modes of the probability density functions range from 8.00 m·s⁻¹ for \( p = 1/10 \) to 9.67 m·s⁻¹ for \( p = 1/5 \). They broadly coincide with the maxima of the power efficiencies of machines like General Electric 1.6 - 82.5, Senvion MM92, and Mitsubishi MWT95/2.4. For all three periods, the probability \( P_1 \) is very low, but the \( P_3 \) is very high (see Table 9). The combination of these issues leads to extraordinarily high capacity factors. As illustrated in Figure 19, the average capacity factor ranges for Period I from 48.7% at \( R_p = 0.133 \) for \( p = 1/10 \) to 63.4% at \( R_p = 0.303 \) for \( p = 1/5 \), for Period II from 52.4% at \( R_p = 0.145 \) for \( p = 1/10 \) to 67.5% at \( R_p = 0.334 \) for \( p = 1/5 \), and for Period III from 44.9% at \( R_p = 0.118 \) for \( p = 1/10 \) to 59.4% at \( R_p = 0.271 \) for \( p = 1/5 \). Again, the results obtained for Periods II and III indicate a slight effect due to the near-surface wind-speed stilling (see Figure 18).

According to the Alaska Energy Data Gateway (https://akenergygateway.alaska.edu/community-data-summary/1418448/), between 2008 and 2013, the average power consumption (residential, commercial, and other) was about 2509 MWh. This means that one of the smaller wind turbines considered here would already be able to supply the community’s power demand for much of the year without much support by Diesel generators. (Nevertheless, a spinning reserve is intended to protect the system against unforeseen events such as generation outages, sudden load changes or a combination of both.) The near-surface air temperature ranges from −25.0˚C observed on January 30, 2000 to 25.0˚C observed on July 13, 1960 [103]. Based on the period from 1971 to 2000, the lowest mean monthly minimum temperature is −5.0˚C (February) and the highest mean monthly temperature is 8.6˚C (August) [103]. Thus, the conditions of the common operating temperature range are usually fulfilled. Icing of the rotor blades, however, may occur during the cold season.

There is, however, a significant drawback. The Alaska-breeding population of Steller’s Eider currently listed as threatened under the Endangered Species Act (ESA) and a State of Alaska species of special concern, regularly occurs on Izembek National Wildlife Refuge, near Cold Bay [104].

With respect to all three periods, the differences in wind-power generation between St. Paul Island located in the Bering Sea and Cold Bay are of secondary importance. St. Paul Island has a wind-power class of 6 as well. The probability
Figure 19. Capacity factor averaged over all wind turbines considered in this study versus the ratio $R_p = P_1/(P_2 + P_3)$ at first-order weather stations (a) Barrow, (b) Big Delta, (c) Kotzebue, (d) Nome, (e) Bethel, (f) King Salmon, (g) Juneau, (h) Annette, (i) St. Paul Island, (j) Kodiak, and (k) Cold Bay as well as $p = 1/10$, $p = 1/7$, and $p = 1/5$.

density functions determined for all three shear exponents and all three periods slightly differ from those of Cold Bay. Compared with those of Cold Bay, the modes are slightly shifted to lower wind speeds leading to a slightly higher probability $P_1$ and a slightly lower probability $P_3$. Thus, the capacity factors determined for St. Paul Island are somewhat lower than the corresponding ones of Cold Bay. As illustrated in Figure 19, the average capacity factor ranges for Period I from 44.6% at $R_p = 0.106$ for $p = 1/10$ to 59.8% at $R_p = 0.260$ for $p = 1/5$, for Period II from 46.3% at $R_p = 0.102$ for $p = 1/10$ to 62.0% at $R_p = 0.267$ for $p = 1/5$, and for Period III from 42.3% at $R_p = 0.107$ for $p = 1/10$ to 56.8% at $R_p = 0.250$ for $p = 1/5$. Again, the results obtained for the Periods II and III indicate a marginal effect due to the near-surface wind-speed stilling (see Figure 18).

Based on the Alaska Energy Data Gateway, the average power consumption
(residential, commercial and others) from 2009 to 2013 was about 3945 MWh mainly generated by using oil. The smaller wind turbines considered in this study would be able to supply the community’s power demand for much of the year without much support by Diesel generators. The near-surface air temperature ranges from −28.3°C observed on March 14, 1971 to 18.9°C observed on August 25, 1987 [103]. Based on the period from 1971 to 2000, the lowest mean monthly minimum temperature is −7.3°C (February) and the highest mean monthly temperature is 7.3°C (August) [103]. Thus, the conditions of the common operating temperature range are usually fulfilled. Nevertheless, icing of the rotor blades may occur during the cold season.

St. Paul Island has a wind power history. As stated on its website (http://www.tdxpower.com/projects-commercial), the Tanadgusix Corporation (TDX) contracted with Northern Power designed and installed a wind/diesel system on St. Paul Island. The site is an airport and industrial complex with airline offices, equipment repair, and storage facilities. After completion, TDX Power began operating the first Native owned and operated independent, hybrid wind/diesel power plant in Alaska. Formally commissioned in 1999, this project capitalized on the emerging hybrid technology as a way to combat escalating fossil fuel prices. The major generation for the hybrid system is provided by a 225-kW Vestas V27 wind turbine. The system supplies electricity and space heat to an 88,000 SF industrial/airport facility and has reduced fuel consumption at the complex by 45%. Future plans involve expanding the wind power capacity and heating infrastructure. A total of 3 Vestas V27 wind turbines are currently installed, and a project is underway to connect the microgrid to the St. Paul municipal utility grid.

In its Systems Performance Analyses of Alaska Wind-Diesel Projects of 2009 (DOE/GO-102009-2712), the US Department of Energy (DOE) pointed out that in 2004 the wind turbine had a non-scheduled availability of 100% and a capacity factor of more than 40% and that the operating wind turbine has experienced a capacity factor of almost 32%. Using the power curve of the Vestas V27 machine taken from Mölders et al. [35] and assuming a hub height of \( z = 37 \) m we predicted the wind-power output for St. Paul Island for the purpose of comparison. Based on the daily mean wind speeds of Period III, we obtained for the shape parameters and the scale parameters, and the capacity factors following values: \( k_w = 2.279 \) and \( c_w = 8.320 \text{ m} \cdot \text{s}^{-1} \) for \( p = 1/10 \), \( k_w = 2.271 \) and \( c_w = 8.794 \text{ m} \cdot \text{s}^{-1} \) for \( p = 1/7 \), and \( k_w = 2.284 \) and \( c_w = 9.497 \text{ m} \cdot \text{s}^{-1} \) for \( p = 1/5 \), respectively. This means that the results of our analyses substantially agree with the results of this DOE report. In this case, the probability \( P_1 \) ranges from 10.3% for \( p = 1/5 \) to 13.8% for \( p = 1/10 \), \( P_2 \) ranges from 82.7% for \( p = 1/5 \) to 83.5% for \( p = 1/10 \), and \( P_3 \) ranges from 2.7% for \( p = 1/10 \) to 6.9% for \( p = 1/5 \), where the true value of \( v_{ct} = 3.6 \text{ m} \cdot \text{s}^{-1} \) and \( v_{pr} = 14.6 \text{ m} \cdot \text{s}^{-1} \) of the Vestas V27 wind turbine were considered. The modes of the probability functions are ranging from 6.33 m∙s−1 for \( p = 1/10 \) to 7.33 m∙s−1 for \( p = 1/5 \).
The capacity factor ranges from \( C_{F,t} = 31.7\% \) at \( R_p = 0.032 \) for \( p = 1/10 \) to and \( C_{F,t} = 40.7\% \) at \( R_p = 0.077 \) for \( p = 1/5 \).

Again, there is a significant drawback. St. Paul Island is home to millions of seabirds nesting in colonies along its steep shores. Rare birds are found here each year during spring migration. Also, St. Paul Island is considered a top North American bird watching destination [34].

Barrow located on the Chukchi Sea coast is the northernmost city of the United States. It has a remarkable wind-power potential expressed by the wind-power class of, at least, 3, termed as “fair”. The probability density functions for all three shear exponents determined for all periods notably differ from those of Cold Bay. There is a shift in the modes by 2 m/s\(^{-1}\) or so to lower mean wind speeds. This leads to a remarkably higher probability \( P_2 \) and a notably lower probability \( P_3 \). Thus, the capacity factors determined for Barrow are notably lower than the corresponding ones of Cold Bay and St. Paul Island. As shown in Figure 19, the average capacity factor ranges for Period I from 30.1\% at \( R_p = 0.026 \) for \( p = 1/10 \) to 47.2\% at \( R_p = 0.126 \) for \( p = 1/5 \), for Period II from 29.2\% at \( R_p = 0.014 \) for \( p = 1/10 \) to 47.4\% at \( R_p = 0.102 \) for \( p = 1/5 \), and for Period III from 29.4\% at \( R_p = 0.033 \) for \( p = 1/10 \) to 45.6\% at \( R_p = 0.134 \) for \( p = 1/5 \). Since the decrease in the near-surface horizontal wind speed is marginal, the corresponding effect is negligible.

Based on the Alaska Energy Data Gateway, the average power consumption (residential and commercial) between 2008 and 2013 was about 48,909 MWh. The electricity was mainly produced using natural gas from nearby gas, only a very small amount was generated using oil. A power consumption of about 50 GWh would require numerous medium-scale wind turbines.

The generation of wind power at Barrow is strongly limited by the operating temperature range. The near-surface air temperature ranges from \(-48.9^\circ\text{C}\) observed on February 3, 1924 to 26.1\(^\circ\text{C}\) observed on July 13, 1993 [103]. Based on the period from 1971 to 2000, the lowest mean monthly minimum temperature is \(-30.0^\circ\text{C}\) (February) and the highest mean monthly temperature is 8.1\(^\circ\text{C}\) (July) [103]. Consequently, Barrow would require cold climate versions of wind turbines with limits of \(-30^\circ\text{C}\) and lower. Senvion’s MM92 CCV nearly fulfills this requirement. Icing of the rotor blades, however, may occur during the cold season. Beside the low temperature range, Barrow’s landscape has a great deal of lakes, ponds, and birds migrating. Wind turbines could impede the wildlife in the area by disrupting the migration and habitats of these animals. Based on these facts, we do not recommend the use of wind power at Barrow under the current conditions.

Kotzebue located at the north-western corner of the Baldwin Peninsula in the Kotzebue Sound, has a notable wind-power potential expressed by the wind-power class of 4, termed as “good”. The wind-power density and average wind speed at hub height are relatively high signifying that it could generate a lot of power. The probability density functions determined for all three shear exponents...
ents and all three periods, however, notably differ from those of Cold Bay. There is a notable shift in the modes to lower mean wind speeds ranging from 2 m∙s^{-1} to 4 m∙s^{-1} or so. Thus, \( P_1 \) is notably higher and \( P_3 \) is notably lower, and, hence, the capacity factors determined for Kotzebue are notably lower than the corresponding ones of Cold Bay and St. Paul Island. As illustrated in Figure 19, the average capacity factor ranges for Period I from 26.8\% at \( R_p = 0.051 \) for \( p = 1/10 \) to 40.7\% at \( R_p = 0.145 \) for \( p = 1/5 \), for Period II from 31.0\% at \( R_p = 0.053 \) for \( p = 1/10 \) to 46.3\% at \( R_p = 0.164 \) for \( p = 1/5 \), and for Period III from 23.1\% at \( R_p = 0.048 \) for \( p = 1/10 \) to 35.3\% at \( R_p = 0.129 \) for \( p = 1/5 \). The results obtained for the Periods II and III indicate a notable effect due to the near-surface wind-speed stilling (see Figure 18).

According to the Alaska Energy Data Gateway, the average power consumption (residential, commercial, and other) between 2009 and 2013 was about 20510 MWh. An average amount of 1955 MWh is related to wind power which corresponds to 9.5\% (but 15.8\% in 2013) of the net generation of electricity.

According to DOE’s Systems Performance Analyses of Alaska Wind-Diesel Projects of 2009 (DOE/GO-102009-2711) the wind farm consists of fifteen 50-kW AOC 15/50 and Entegrity Wind Systems EW50; one 100-kW Northern Power Systems Northwind 100/19 A, and one remanufactured Vestas V17, \( i.e.\), the total rated power is 0.925 MW. However, a power consumption of about 20 GWh would require some medium-scale wind turbines.

The near-surface air temperature ranges from −50.0˚C observed on March 16, 1930 to 29.4˚C observed on June 22, 1991 \[103\]. Based on the period from 1971 to 2000, the lowest mean monthly minimum temperature is −23.3˚C (February) and the highest mean monthly temperature is 15.6˚C (July). Thus, Kotzebue would require cold climate versions of wind turbines with limits of −30˚C. Icing of the rotor blades may occur during the cold season.

About 90 miles east of Kotzebue lies the Selawik National Wildlife Refuge. During the short Arctic summers, large numbers of white-fronted geese and tundra swans arrive along with sandhill cranes and a horde of other shorebirds.

Lastly, Bethel is the largest community on the Kuskokwim River, approximately 80 km upstream from where the river flows into Kuskokwim Bay. Bethel has a remarkable wind-power potential expressed by the wind-power class of, at least, 3 termed as “fair”. The probability density functions for all three shear exponents determined for all periods notably differ from those of Cold Bay. There is a shift in the modes by more than 2 m∙s^{-1} to lower mean wind speeds. Thus, \( P_1 \) is remarkably higher and \( P_3 \) is notably lower, and, hence, the capacity factors determined for Bethel are notably lower than the corresponding ones of Cold Bay and St. Paul Island. The average capacity factor ranges for Period I from 24.9\% at \( R_p = 0.012 \) for \( p = 1/10 \) to 41.3\% at \( R_p = 0.082 \) for \( p = 1/5 \), for Period II from 29.2\% at \( R_p = 0.013 \) for \( p = 1/10 \) to 46.0\% at \( R_p = 0.105 \) for \( p = 1/5 \), and for Period III from 23.0\% at \( R_p = 0.013 \) for \( p = 1/10 \) to 38.3\% at \( R_p = 0.077 \) for \( p = 1/5 \) (see Figure 19). As shown in
Figure 18, the results obtained for Periods II and III indicate a remarkable effect due to the near-surface wind-speed stilling.

According to the Alaska Energy Data Gateway, the average power consumption (residential, commercial, and other) between 2008 and 2013 was about 39749 MWh. A power consumption of about 40 GWh would require numerous medium-scale wind turbines.

The near-surface air temperature ranges from −44.4˚C observed on January 28, 1989 to 30.6˚C observed on August 9, 2003 [103]. Based on the period from 1971 to 2000, the lowest mean monthly minimum temperature is −17.4˚C (January) and the highest mean monthly temperature is 17.3˚C (July). Thus, the conditions of the common operating temperature range are usually fulfilled. Nevertheless, icing of the rotor blades may occur during the cold season.

A potential problem with Bethel is that it is surrounded by the Yukon Delta National Wildlife Refuge which supports one of the largest aggregations of water birds in the world. Thus, wind turbines could strongly impact the wildlife in that area by killing countless birds.

Based on our study, one may conclude that wind-stilling affects wind-power generation in Alaska to a notable degree. Thus, prior to installing new wind farms, assessments of suitability for power generation should look at the entire record of available data to identify trends in $P_1$, $P_2$, and $P_3$. Obviously, the distribution of these probabilities affects productivity. These aspects may also optimize the choice of turbine and sustainability of wind power. Also, like in the permitting process of power plants and other industrial complexes, a full environmental impact assessment must be performed to protect the subsistence lifestyle in the immediate area of the potential farm, wildlife, eco-systems and local climate. While the assessment of the impacts on endangered species, migrating birds and birds that are part of a subsistence lifestyle is straight forward, assessment of the impacts on local climate requires numerical modeling techniques. The mixing of air due to the rotor blades and the consequent more frequent neutral conditions alter the cloud and precipitation formation in the near-field. Such changes in the water cycle are known to affect ecosystems again with potential impacts on birds, fish and game and hence a subsistence lifestyle.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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G. Kramm et al.

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