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Atmospheric Irrigation with Wind Turbines

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Abstract. In this paper, atmospheric irrigation with wind turbines is proposed. This technology addresses the problem of water scarcity by enhancing the natural water circuit in the atmosphere with wind turbines. There are three different operating modes conceivable for this technology. In two of these the wind turbines interact with the ground in their near wake. The third operating mode is the one which is discussed in this paper, and it aims at transporting water potentially over long distances. The basic working principle, the utilized physical phenomena and the basic design of the technology are introduced. The equations governing the hydraulic and the hydrological effects are presented. The goal of this paper is to quantify the necessary power and the necessary amount of water when wind turbines humidify a certain volume of air in the atmosphere. For this purpose, the power and water demand are assessed, both in a generalized manner and for a realistic scenario. It is concluded that the proposed system can achieve the objective in most wind speed conditions. However, the required amount of water is substantial. Therefore, an alternative source of fresh water has to be found when the system is used on a comparably large scale.

1. Introduction

Humankind tries to mitigate the human-made climate change with measures like substituting conventional power plants by wind turbine (WT) generators. As a consequence of this transition to renewable energies, WTs can be found all over the world. As a consequence of the climate change, extreme weather conditions like drought become more frequent.

To tackle the problem of aridity and too seldom precipitation, a system is currently being developed, which enables WTs to emit water into the atmosphere, in order to enhance the natural water circuit. For simplicity, this system is called irrigation system (IS) in the following.

The IS can be applied in three different operating modes: (i) direct irrigation in the near wake, (ii) local cooling in the near wake and (iii) water transport over longer distances to enhance precipitation in remote locations. Irrigation via the atmosphere is considerably more social than channeled fresh water supply, as it disperses water without discrimination not only for human beings, but also for nature. Flat water provision improves soil quality and fosters growth of plants. Plants counteract climate change by capturing CO_2 and by storing fresh water.

Forest, bush and peat fires are supported by aridity. They accelerate global warming by releasing large amounts of CO_2, and they magnify aridity by destroying natural fresh water reservoirs. Fighting such fires from the ground is hard. Instead, increased air humidity and water drops from the atmosphere are much more effective. Therefore, the IS can be applied for preventing and fighting forest, bush and peat fires.

The IS is most suitable for bringing fresh water from estuaries of rivers back into the natural water circuit, before it arrives at the sea, where it mixes with saltwater, and hence, becomes undrinkable and unusable for most organisms living onshore. However, the application of the IS is not limited to arid areas in the classical sense. It can also be applied to store fresh water in the form of snow and ice in cold regions. By applying it for replenishing glaciers, the IS helps storing fresh water, increasing the albedo of the surface of the earth and slowing down the rise of the sea level [1].

If fresh water from estuaries is used with the IS, onshore wind is required. Many sites on earth provide suitable conditions; either because they exhibit regular and strong thermal sea breezes, or because they are affected by global wind systems, like the prevailing westerlies, blowing onshore.

2. Description of the Irrigation System

2.1. Basic Principles of Atmospheric Irrigation

The basic idea of atmospheric irrigation with WTs is that WTs disperse water in the atmosphere with their rotor blades. Modern WTs have large rotor areas on high towers. Hence, their rotor blades sweep large vertical areas in the air, through which the wind blows perpendicularly. Consequently, water emitted by the rotor blades is carried away by the wind much more effectively than water from horizontal water surfaces on the ground, e.g. the surface of the sea, or the surface of lakes and rivers.

Figure 1 illustrates the principle, where a WT emits fresh water from the estuary of a river. This WT stands for a number of WTs in a wind farm. It is obvious that the amount of water, which can be emitted, increases with the number of WTs. Several WTs next to each other (seen from the wind direction) increase the width of the layer of air which is enriched with water. Several WTs behind each other (in wind direction) can lift the humidity of the air to a higher level, and hence, bring the air closer to saturation with water vapor.

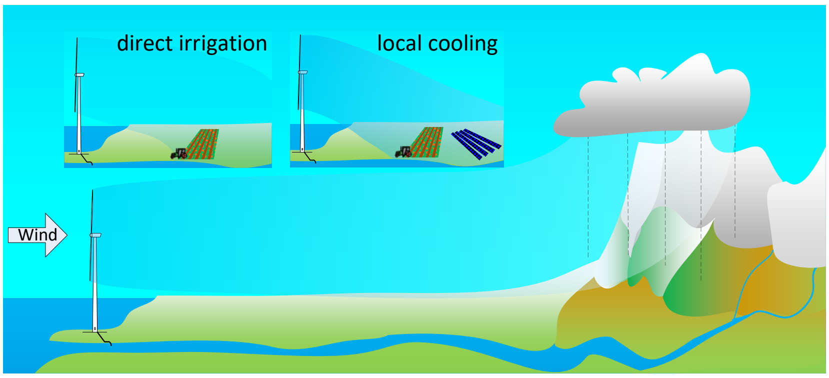

Figure 1 WT emits fresh water from a river. Onshore wind carries the vaporized water inland. Mountains deflect the humidified air vertically, which causes the air to cool down and the water to condense. The small subplots show the other two fields of application of the IS.

When the IS emits water vapor into the air, the humidity in the air behind the rotor is higher than the humidity in the air in front of the rotor. In the scenario shown in Figure 1, the wind carries the water vapor inland where it hits a mountain ridge, which deflects the air vertically. The temperature of the air drops with increasing altitude. When the air has reached the dew point, the water vapor condenses, which leads to fog or clouds. In the example introduced here, the wind is utilized for transporting water over long distances in the form of vapor.

Vaporization extracts energy from the air. Hence, the air in the wake of a WT with IS is cooler than the air in front of the WT. This local cooling reduces drying out of the soil and of the vegetation in the area behind the WT.

If the water is needed in closer proximity of the emitting WT, full vaporization is dispensable. In this direct irrigation, the wake of the WT is full of water droplets, which are carried by the wind but gradually drop to the ground.

2.2. Basic Design of the Irrigation System

The IS is most efficient, when it is applied in modern state-of-the-art WTs, which are characterized by high towers and long rotor blades. Such WTs are most suitable for bringing water into the atmosphere in considerable height above ground and via a large vertical area, through which the wind can blow. Therefore, for the purpose of illustration and quantification, throughout this paper a 4 MW variable speed WT is considered. Properties and parameters of this WT are stated in this paper whenever they are needed in the context of the discussion.

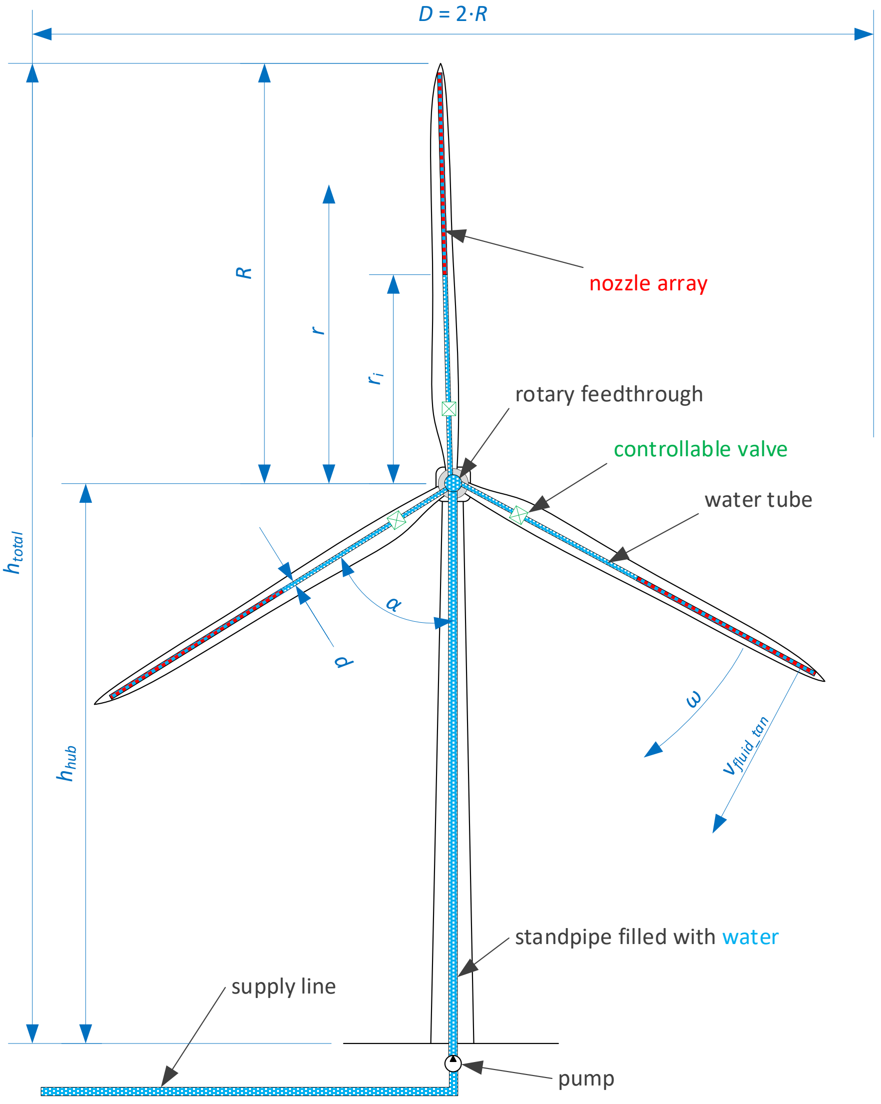

Figure 2 Schematic representation of a WT with the major components of the IS.

The IS with its major components is shown in Figure 2 and briefly discussed in the following. As shown in Figure 2, water has to be brought to the WT via a supply line. In the tower bottom, the water has to be pressurized to be transported into the nacelle via a stand pipe inside the tower.

From the nacelle, the water has to be brought into the vertically rotating rotor of the WT via a rotary feedthrough. Inside the hub of the rotor, the water tube is split up into individual tubes per rotor blade.

The volumetric water flow rate, and hence, the pressure at the nozzles in each blade, can be controlled with controllable valves in each individual blade.

From the rotor blades, the water is emitted into the atmosphere through a large number of nozzles. These nozzles are grouped to nozzle arrays, which are located on the suction side and on the trailing edge of the airfoil, as can be seen in Figure 3. The location and number of nozzles, as well as the droplet size and the volumetric flow rate of the nozzles on the suction side, are determined by the best possible effect of water emission on the boundary layer [2]. Thereby, the aerodynamic performance of the blades is improved by the IS, which can increase the energy yield of the WT and reduce the mechanical loads on the structure of the WT. Increasing the energy yield improves the profit for the WT owner. Reducing mechanical loads saves material in the rotor blades and in the entire support structure of the WT. Hence, also load reduction is ultimately an aspect of economic efficiency. In state-of-the-art WTs, active elements for improving the aerodynamics are still largely avoided, because these increase system complexity, more than they reduce costs [3]. Similar to the popular and commonly used passive vortex generators, blowing a fluid into the boundary layer of the suction side, also adds energy to the boundary layer and reduces the risk of flow separation. Different of such blowing techniques were tested, which allowed proving their positive effects on the aerodynamic drag [4]. The complexity of such active systems has to date prevented their application in commercial WTs, as it would make WTs uneconomic.

The IS proposed here also blows a fluid into the boundary layer of the suction side of the airfoil. However, irrigation is the primary task of this system and potential improvements of the aerodynamics are only side effects. Therefore, the system does not have to pay for itself with more energy yield, or with material savings by reducing the loads on the WT. Instead, it amortizes via its irrigation service, if there is a remuneration system in place. Alternatively, the additional investment is justified by the positive effect for nature and society.

The nozzles on the trailing edge of the airfoil emit the remaining water and will, as a side effect, reduce the aerodynamic noise emission from trailing edge vortices. At the trailing edge, the fast air from the suction side meets the slower air from the pressure side, which leads to turbulences, and hence, aerodynamic noise emission. The kinetic energy in these turbulences can be reduced when the air, with its low viscosity, is mixed with water, which has a considerably higher viscosity [5].

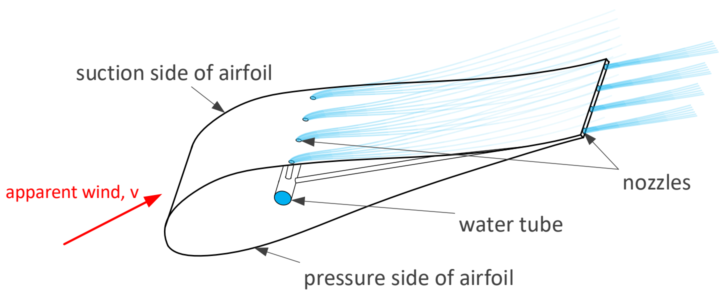

Figure 3 Section of a rotor blade with water tube inside the blade and with nozzle array in the surface of the suction side and on the trailing edge of the airfoil.

Figure 2 suggests that the nozzle arrays not necessarily have to stretch the whole length of the rotor blades. In section 2.3 it is discussed that, for the purpose of vaporization, the nozzles work best when located at larger rotor radii.

2.3. Physical Principles of the Irrigation System

In this section the working principle of the IS is discussed qualitatively. The IS can work in two modes:

- It can emit water droplets into the atmosphere, which are carried away by the wind and which gradually fall down to the ground in the wake of the WT. See "direct irrigation" in Figure 1.
- It can vaporize water at the nozzle arrays and thereby increase the humidity (for the purpose of "water transport over long distances") and decrease the temperature of the air behind the rotor (for the purpose of "local cooling", see Figure 1).

The physical principle of emitting spray mist, i.e. droplets, is straight forward, and therefore, only the physical principle of the second mode, i.e. vaporization, is discussed in the following.

Vaporization is the transition from the liquid state to the gaseous state below the boiling temperature. In vaporization, water molecules leave the liquid water if their kinetic energy suffices for overcoming the attraction, which their neighbouring molecules exert on them. This can happen until the air above the water surface is saturated with water vapor, i.e. its relative humidity has reached 100 %. The following factors determine vaporization [6].

2.2.1. Water temperature. The kinetic energy in the water molecules rises with increasing water temperature; hence, high water temperature facilitates vaporization. It would be advantageous to emit warm water through the nozzles. If available, warm surface water from e.g. a river could be used. From an energetic point of view, it does not seem desirable to heat the water electrically with the power generated by the WT. From the analysis presented in sections 2.7 and 3.2, it also becomes obvious that there is only limited electric excess power available for heating the water. Alternatively, pre-heating the water with solar energy could be applied.

2.2.2. Air humidity and air temperature. With increasing humidity, the air approaches saturation with water molecules. At the dew point, the air is fully saturated and cannot absorb any more water molecules. The saturation amount increases exponentially with increasing temperature; hence, high air temperature and low air humidity facilitate vaporization. Neither the humidity nor the temperature of the air in front of the rotor of the WT can be influenced. Which air-humidity/air-temperature combination is advantageous, depends on the considered scenario; more on this in section 2.7.

2.2.3. Air pressure. The air pressure above a water surface has an influence on the kinetic energy, which water molecules need to have to be able to leave the water surface. Hence, low air pressure facilitates vaporization. It is obvious that the ambient pressure in the atmosphere cannot be manipulated. However, the airfoil of a rotor blade produces lift because of the pressure drop from pressure side to suction side [7]. Hence, for the sake of vaporization, it is advantageous to locate the nozzles on the suction side of the rotor blades.

2.2.4. Air speed. The higher the air speed, the more water molecules have to be brought into a volume unit of air to saturate it with water, before it has passed the water surface. Hence, high air speed facilitates vaporization. The rotation of the rotor leads to extreme air speeds, in most locations along a rotor blade.

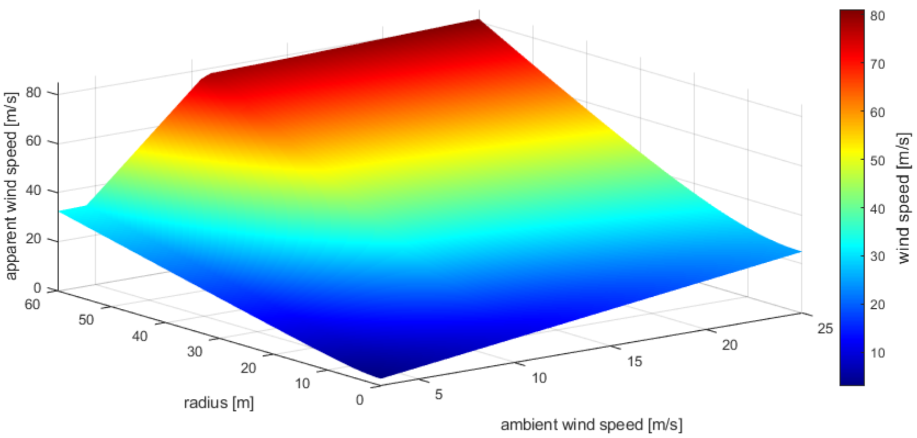

Figure 4 Apparent wind speed perceived by a WT rotor blade, plotted versus rotor radius and ambient wind speed.

The rotor of a WT is exposed to the ambient wind speed, v_0, which ideally hits the rotor plane perpendicularly. Since the rotor rotates, the single rotor blades also experience a wind speed component, which results from the rotation of the rotor at radius r and angular speed ω. These two perpendicular wind vectors add up to the apparent wind speed, v, see equation (1).

$$v = \sqrt{(\omega \cdot r)^2 + v_0^2} \tag{1}$$

Equation (1) reveals that the rotating wind increases with the radius. Figure 4 visualizes the apparent wind speed along the blade of a rotor with 60 m radius. The considered WT is full variable speed and its power versus speed characteristic allows for speed variations in part load operation of about 58 %.

Figure 4 shows that for the purpose of vaporization of water, there are extremely favourable wind speeds along the largest part of a rotor blade in most ambient wind speed conditions.

2.4. Hydraulic Description of the Irrigation System

Pressure, p, is exerted on the water with its density, ρ, when it is pumped through the IS from tower bottom to the nozzles. The pump in the tower bottom has to lift the water to hub height, h_{hub}, see Figure 2, which shows some of the variables and parameters mentioned throughout this paper. At h_{hub}, the water enters into the rotating rotor. Therefore, the following pressure consideration starts from the centre of rotation and takes the pressure on h_{hub} as the basis.

In general, there are five pressure components that have to be considered in vertically rotating systems: external pressure like the atmospheric pressure or the pressure from a pump, p_p, the pressure from gravitation, p_g, pressure from centrifugal acceleration, p_c, the pressure from variations in the kinetic energy in the moving water, p_{dyn}, and pressure losses from friction, p_f.

$$p = p_p + p_g + p_c + p_{dyn} - p_f \tag{2}$$

The pump pressure is variable and can be controlled with the pump in the tower bottom. The pressure from gravitational acceleration, g, depends on the position of the considered rotor blade, α. (When a blade points vertically downwards, α is zero.) It also depends on the considered location along the blade, i.e. on the distance from the centre of rotation, r. The centrifugal pressure depends on the angular speed of the rotor, ω, and also on r. A dynamic pressure occurs if the flow speed of the water, v_{fluid}, changes from one value v_{fluid1} to another value v_{fluid2}. Pressure losses from friction depend on v_{fluid} and on the friction coefficient of the rotary feedthrough, valves, joints and other non-straight conduits, ξ. Figure 2 shows, that the system is dominated by long tubes, hence, also the friction losses of all tubes have to be considered with the Darcy friction factor, λ. Equation (3) is the extension of equation (2).

$$p = p_p + \rho \cdot g \cdot r \cdot \cos(\alpha) + \frac{\rho}{2} \cdot \omega^2 \cdot r^2 + \frac{\rho}{2} \cdot \left(v_{fluid1}^2 - v_{fluid2}^2\right) - \frac{\rho}{2} \cdot v_{fluid}^2 \cdot \left(\xi + \lambda \cdot \frac{r}{d}\right) \tag{3}$$

Equation (3) allows calculating the pressure at the individual nozzles. Nozzles require a particular pressure range for emitting water with the desired droplet size, and their volumetric flow rate depends nonlinearly on the pressure. Hence, the pressure in the rotary feedthrough is controlled with the pump in the tower bottom, which leads to p_g. The pressure in the individual blades can further be controlled with the valves in the blades, where pulse-width-modulation can be applied for fine-tuning the pressure as a function of α.

In this study, however, the focus is not on the flow in the individual nozzles, but on the overall water turnover and the power demand of the whole IS. For this sake, the effect of friction is neglected here, as it is assumed that the hydraulic components are dimensioned sufficiently to only cause moderate friction at the maximum volumetric flow rate, Q, which can be derived from v_{fluid} and cross-sectional area, A, of the conduit.

$$Q = v_{fluid} \cdot A \tag{4}$$

Any Q lower than the maximum, invariably leads to considerably lower friction losses, as p_f is a function of v_{fluid}^2. In the rotor blades, the water is emitted along the nozzle array; hence, the water volume in the tube decreases with increasing radius, $Q(r)$. In order to have the minimum tube mass and water mass in the blade, the tube in the blade is tapered by decreasing the tube diameter, $d(r)$, with increasing radius, such that v_{fluid} in the tube stays constant along the whole blade length. The volumetric flow rate, $Q(r)$, decreases linearly from the beginning of the nozzle array, r_i, to zero at the largest radius, R.

$$Q(r) = v_{fluid} \cdot \frac{\pi}{4} \cdot d(r)^2 \tag{5}$$

Averaging the pressure from gravitation over a whole revolution of the rotor yields zero. Hence, for the sake of the assessment of water turnover and power demand of the whole IS, p_g can also be neglected.

The dynamic pressure occurs mainly perpendicular to the tubes, because the water gains tangential speed, v_{fluid_tan}, as it travels to larger radii. Consequently, in this study, the centrifugal pressure and the dynamic pressure are the only ones, which are considered in the conduits of the rotor.

2.5. *Hydrological Description of the Irrigation System*

The amount of water vapor, which the air in the atmosphere can carry, is a function of the temperature. At ambient temperature $\vartheta = 20°C$, air is saturated with water vapor, when it carries $f_{max} = 17.3$ g water per m³ air. For other temperatures, f_{max} can either be retrieved from literature, or it can be roughly calculated via the Magnus equation, which derives the saturation vapor pressure, p_d, for a range of temperatures above 0°C [8]:

$$p_d = 6.112hPa \cdot e^{\left(\frac{17.62 \cdot \vartheta}{243.12°C + \vartheta}\right)} \quad (6)$$

The following equation allows deriving f_{max} in g/m³ from p_d, the gas constant of air $R_w = 461.52$ in J/(kg K) and the temperature in Kelvin, T.

$$f_{max} = \frac{p_d \cdot 1000}{R_W \cdot T} \quad (7)$$

A particular mass of water per m³ air, f, leads to a certain relative humidity, φ:

$$\varphi = \frac{f}{f_{max}} 100\% \quad (8)$$

Although a WT has a circular rotor area, and although the nozzles only sweep an even smaller ring-shaped area (Figure 2), the IS is demanded to raise the humidity to the desired value in a larger air volume. This volume is assumed to have a rectangular cross-section with the width of the rotor diameter, D, and the height of the WT, h_{total}, see Figure 2. It is assumed that turbulences in the wake of the WT cause a mixing of humidified air with drier ambient air. Hence, it is deemed that humidifying only the air in the cylindrical wake tube to the desired value would not be sufficient. The air volume, V_{air}, in m³, which has to be humidified per second is

$$V_{air} = D \cdot h_{total} \cdot v \quad (9)$$

With the required water mass derived with equation (8) and with the density of water ($\rho = 1000$ kg/m³), the water volume that has to be emitted per second can be calculated. Moving this water mass requires power, which is quantified in the next section.

2.6. *Energy and Power of the Irrigation System*

The IS consumes power, which either the WT has to produce aerodynamically, or which has to be imported electrically from the grid. The power consumption comprises three components: (i) for lifting the water to hub height and for accelerating the water (ii) radially and (iii) tangentially in the blades.

To get the water into the nacelle, a pump in the tower bottom has to lift the water with its mass, m, to hub height, h_{hub}, against the gravitational acceleration, g, which increases its potential energy:

$$E_{pot} = m \cdot g \cdot h_{hub} \quad (10)$$

Considering volumetric flow rate and density instead of mass, allows calculating the power of the pump, P_{pump}. In the absence of an applicable overall efficiency, η, of the pumping system, P_{pump} represents the minimum necessary power, which has to be provided electrically at the terminals of the pump motor. I.e. in this study η is considered to be 1.

$$P_{pump} = \frac{E_{pot}}{t}\eta = Q \cdot \rho \cdot g \cdot h_{hub} \cdot \eta \quad (11)$$

Once the water enters into the tubes of the rotor blades, it is accelerated in radial direction by centrifugal pressure, p_c, see equation (3). Consequently, a centrifugal force, F_c, is exerted on the fluid in the tube with its diameter, $d(r)$:

$$F_c = p_c(r) \cdot \frac{\pi}{4} \cdot d(r)^2 \quad (12)$$

Driving the water in radial direction requires power, P_c, as the water gains kinetic energy, E_{kin_c}, on its way along the blade, until it is emitted at radius r, after the time, t, of moving in radial direction.

$$P_c = \frac{E_{kin\_c}}{t} = \frac{1}{t} \cdot \int_{r=0}^{r=R} F_c(r) \cdot dr = E_{kin\_c} \cdot \frac{v_{fluid}}{R} \tag{13}$$

The dynamic pressure, p_{dyn}, which arises from a change in fluid speed, see equation (3), occurs perpendicular to the flow direction inside the tube. Because of the rotation, the fluid is accelerated in tangential direction with increasing radius.

$$p_{dyn} = \frac{\rho}{2} \cdot \left(v_{fluid\_tan1}^2 - v_{fluid\_tan2}^2\right) \tag{14}$$

This pressure component acts on the walls of the tubes in tangential direction. Hence, when pumping the water to larger radii, p_{dyn} causes a Coriolis force, which counteracts the rotation of the rotor. Once the water is emitted in the nozzle array, i.e. between r_i and R, the water with its kinetic energy leaves the rotor. The newly to be accelerated water leads to the tangential power demand that results from the Coriolis force:

$$P_{tan} = \int_{r=r_i}^{r=R} Q(r) \cdot p_{dyn}(r) \cdot dr \tag{15}$$

P_c and P_{tan} counteract the driving power from the wind, and hence, reduce the mechanical input power to the WT, while the pump power, P_{pump}, reduces the electric power output of the WT. Hence, the overall power consumption of the IS, P_{irri}, is:

$$P_{irri} = P_{pump} + P_c + P_{tan} \tag{16}$$

2.7. Generalized Quantification of Power Demand and Water Turnover

The above equations reveal, that both the volumetric flow rate, as well as the power demand of the IS, are nonlinear functions of the ambient temperature, the rotor diameter, the wind speed, the rotational speed of the rotor, and they also depend on the hub height, and the wind farm geometry. Furthermore, the ambient and the desired humidity of the air play an important role.

In order to present the effects of the IS in a general manner, the water volume turnover and the power demand of the irrigation are presented as independent of the abovementioned parameters as possible. For this purpose, some parameters are eliminated or set to extreme values: The ambient humidity of the air in front of the rotor is set to the theoretical minimum of 0 %. At the same time, the desired humidity behind the rotor is set to 100 %. The effect of the wind farm geometry is eliminated by assuming that one WT alone has to achieve the desired humidification. To assess the effect of the ambient air temperature, 20°C is compared to the lowest conceivable operating temperature of the IS, i.e. 0°C.

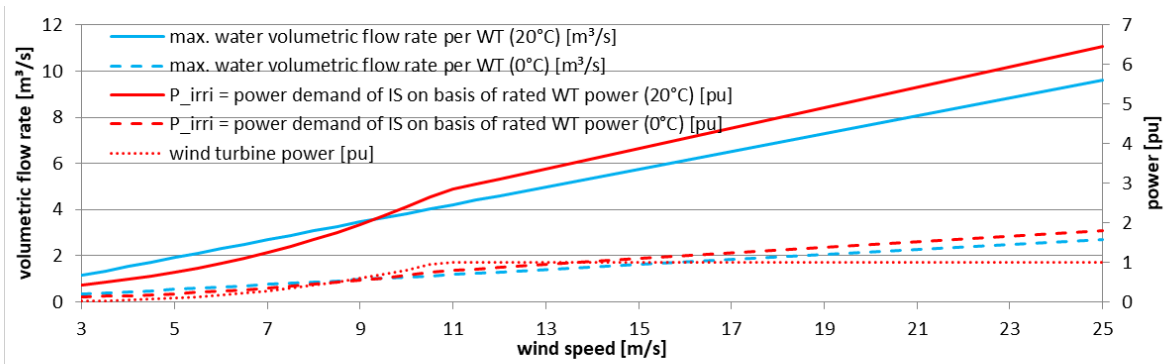

Figure 5 Volumetric flow rate, power demand of IS and aerodynamic power of one WT. The WT raises the humidity from 0 % to 100 %, while the ambient temperature is 0°C (dashed lines) and 20°C (solid lines).

For comparing the aerodynamic power of the WT with the power demand of the IS, the 4 MW WT used in this paper is assumed to have a rotor diameter D = 120 m and a hub height h_{hub} = 125 m. In

Figure 5 (and also in Figure 8), the power is given in per unit (pu) on the bases of the rated power of one WT, i.e. the power in pu is the power in MW divided by 4 MW. The aerodynamic power coefficients of the WT rotor are based on the NREL offshore reference WT [9]. For simplicity, it is assumed that the variation in ambient temperature has no effect on the aerodynamic power of the WT, i.e. the air density is kept at a constant 1.225 kg/m³. To be precise, at 0°C a considerably higher air density, and hence, a higher power in part load operation can be expected. However, this conservative assumption is justified, since also the efficiency of the hydraulic system is neglected, as outlined in the previous sections. In addition, the results in Figure 5 reveal, that these air density driven power increases would have hardly any effect in relation to the power demand of the IS.

The desired increase in humidity enters linearly into the equations. Therefore, the water volume turnover and the power demand shown in Figure 5 can be divided linearly to get the result for any other desired humidity increase. In Figure 5 the solid lines consider ambient temperature of 20°C, which reveals clearly that larger elevations in humidity cannot be accomplished by one line of WTs alone. Instead, a series of WTs, i.e. multiple WTs behind each other in wind direction, is needed to get the water turnover and the power demand of the IS distributed across several WTs.

The comparison between the solid lines (20°C) and the dashed lines (0°C) further reveals that, close to the freezing point, one row of WTs could cause humidification by 100 % in a certain wind speed range. In the following section a realistic scenario is introduced for assessing the capabilities of the IS.

3. Example Scenario for Application of the Irrigation System

In this scenario, the IS is applied in a realistic wind farm setup, where the goal is to transport water over long distances in the form of vapor. Here, realistic relative humidities are assumed, while the equally realistic but demanding ambient temperature of 20°C is applied.

3.1. Description of the Scenario

In a location, which is exposed to onshore wind, the humidity in the air, shall be increased, such that precipitation over land becomes likely. Figure 1 illustrates the scenario, where the shown WT stands for a whole wind farm. The air, which hits the shore, is assumed to have a temperature of 20°C and a relative humidity of 60 %. It is the objective to increase the relative humidity with the IS to 90 %. In this scenario a temperature drop of less than 2 Kelvin suffices for reaching the dew point, i.e. for making precipitation likely.

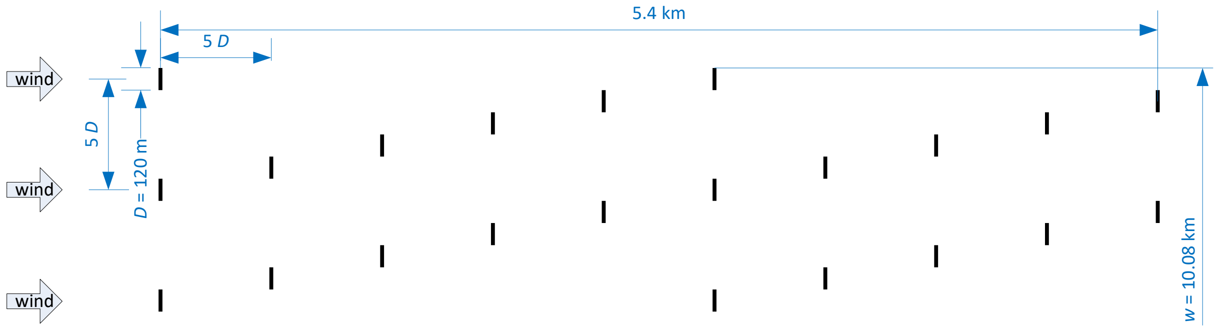

Figure 6 Plan of a fraction of the wind farm, which is 5.4 km wide and 10.08 km long. The WT rotors are shown as black bars.

Fresh water from the estuary of a river is brought to the WTs via a supply line. Hence, the fresh water of the river is used before it becomes unusable saltwater. The water is vaporized and brought back into the natural water circuit by the IS in the WTs of the wind farm.

In order for precipitation to occur, the humidified air must not be diluted too much with drier ambient air. Therefore, the WTs in the wind farm are arranged to create a closed front (Figure 6 and Figure 7), when the wind blows in the direction where precipitation is desired.

The width of the wind farm is chosen such that the objective of reaching 90 % relative humidity is achieved in a 10.08 km long front, to minimize dilution from the sides. The WT parameters mentioned

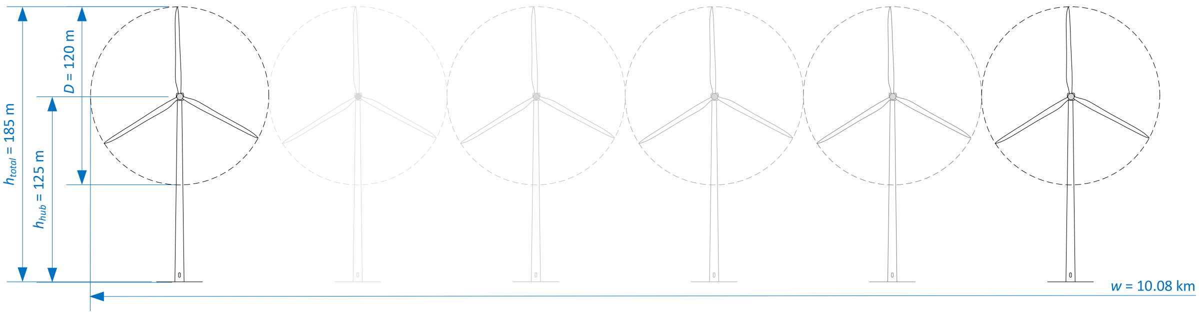

Figure 7 WTs in the different rows of the wind farm, seen from the wind direction. The different grey scales indicate the distance from the viewer, i.e. the columns of the wind farm (compare with Figure 6).

above are also applied here. The WTs are spaced by 5 rotor diameters (D) in longitudinal and in lateral direction. In order to reach the objective, each m³ of air has to be enriched with 5.19 g of water. The task of humidifying the air is distributed to two WTs in each row. Hence, the whole wind farm consists of 168 WTs and each WT has to enrich each m³ of air with 2.595 g of water.

In any wind direction that is different from the one that leads to the area for whose irrigation the wind farm is built, the wind does not hit the wind farm perpendicularly. In these situations, the width of the humidified air volume is reduced, and number of WTs in series is increased. At the same time the WT do no longer create a closed front. I.e. the view as shown in Figure 7 would exhibit gaps. Hence, the wind farm can only achieve its full potential in terms of atmospheric irrigation, when the wind blows in the direction of the area to be irrigated. In any other wind direction, the wind farm is to be used as any conventional wind farm, i.e. for producing electric power only. How often the wind farm operates in irrigation mode is, therefore, not only determined by the need for irrigation, but also by the prevailing wind direction.

3.2. Water Volume Turnover and Power Demand of the Irrigation System

According to equation (9) the humidity shall be raised in a rectangular air volume. Considering the whole wind farm, this volume stretches the wind farm width of w = 10.08 km from the peak of the rotor circle all the way to the ground (h_{total} = 185 m).

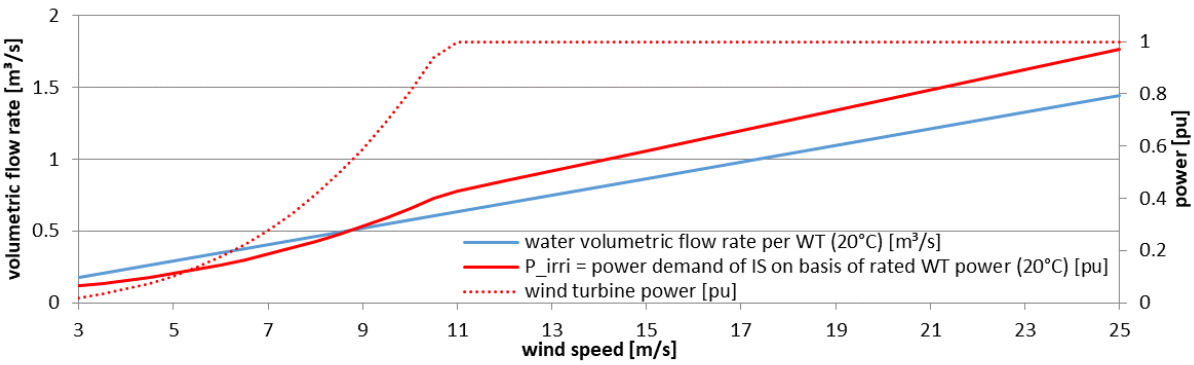

Figure 8 Volumetric flow rate, power demand of the IS and power of one WT in the wind farm of the given scenario.

The water volume that has to be emitted by the wind farm per second can be calculated with equations (7) and (8). Since the considered wind farm comprises 168 WTs, which share this volumetric flow rate, the water turnover per second and WT can be yielded for the different wind speeds, see Figure 8.

For the given scenario, the water demand of the whole wind farm varies between 29 m^3/s at 3 m/s wind speed and 242 m^3/s at 25 m/s wind speed. Comparing these numbers with the average discharge of the largest rivers on earth [10], i.e. the rivers that carry the largest water volumes, it becomes clear that this is only a minor fraction of their water flow rate. Looking at the list of the longest rivers on earth [11] it can be seen that only the larger ones among these rivers carry water in this order of magnitude.

Figure 8 shows that for most wind speeds the IS consumes only a fraction of the WT power. However, below 5.5 m/s the aerodynamic power is not sufficient for covering the power demand of the IS. In all other wind speeds, the WTs can perform both, atmospheric irrigation, as well as power production for the electric power system.

4. Conclusion and Future Work

It can be concluded that the IS is capable of enhancing the natural water circuit in the considered and in many other conceivable scenarios. Since the wind direction has a strong impact on the usability of a wind farm for atmospheric irrigation, the operating mode of the WTs is determined by the wind direction. The IS is only turned on when the wind blows in the direction of the area to be irrigated. For this wind direction, the wind farm layout has to be designed as described above. The use of the IS is further determined by the actual need for irrigation, the ambient air humidity and the current wind speed.

In all other situations, i.e. whenever irrigation is either not desired or not possible, the WTs can operate as normal WTs for producing electric power. Hence, atmospheric irrigation is only one field of application for the WTs. Therefore, depending on the considered site with its specific needs, the WTs can still amortize with produced electric power. The payback period is obviously determined by the site-specific characteristics.

Future will show, whether a remuneration system will be developed for the irrigation service, which would open another source of income for the WT owner. Alternatively, the positive effects for nature and society have to be treated as benefits for the whole society. In this case it is likely that the irrigation service will be financed through taxes.

Causing precipitation in an area, which stretches several km^2, is possible, but requires large amounts of water. Since only few rivers provide sufficient water to serve this purpose, an alternative source of fresh water needs to be found. Therefore, future research has to focus on enhancing the IS to be able to perform seawater desalination with offshore wind farms. Since offshore WTs are invariably grouped in a wind farm, the IS has to avoid excessive emission of salt aerosols, when desalinating seawater.

Atmospheric seawater desalination with WTs has been proposed in literature already [12],[13]. However, these proposals have revealed numerous disadvantages, which have to be avoided when enhancing the IS to seawater desalination. One of these disadvantageous, which are to be avoided with the IS, is that massive emission of salt aerosols is likely to lead to substantial contamination of the leading edges of the airfoils of the WTs. Deterioration of the aerodynamic performance is expected to be the result of airfoil contamination.

Apart from seawater desalination, further future research will focus on direct irrigation, local cooling, as well as on the aerodynamic effects in terms of energy yield, mechanical loads and noise emission.

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