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First experiences with the wind energy plant MoWEC1 and its possible application on the North-west coast of Egypt to irrigate orchards with a low-head bubbler irrigation system

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Abstract

A special kind of wind energy plant, named MoWEC1, was designed with two three-blade rotors running in opposite directions. Each rotor has a diameter of 7.10 meters. The first power curve of the MoWEC1 was measured in a field test with a with a 10-pole permanent-magnet synchronous generator, measuring facilities for current and voltage, heating elements as a load and a digital three-cup anemometer for the wind velocity. The MoWEC1 total average power coefficient was determined at $C_{Pt} = 0.32$.

We chose a water and energy saving irrigation technique suitable for a MoWEC1 application on small orchard farms. According to a comparison of the irrigation techniques, the low-head bubbler irrigation system enabled the economical use of water, and its low operating pressure makes it particularly well-suited for combination with wind energy water pumping systems. The design of this irrigation system is very important, so the computer program LHBIS was written to make low-head bubbler irrigation design simpler and faster than using charts and calculators. Laboratory experiments were conducted to validate this computer program. The program was used to design the low-head bubbler irrigation system for 10 ha at N.W. coast of Egypt.

The average mean monthly MoWEC1 water pumped was calculated at 21,111 m^3/month. This value was enough to irrigate 10 ha of orchards, olives or citrus trees. If only MoWEC1 is used to pump the water, the average cost per m^3 of water would be 3.4 €-Cents.

Keywords: Wind energy, mobile wind energy converter, MoWEC1, irrigation techniques, low-head bubbler irrigation system, computer program LHBIS, N.W. coast of Egypt

Zusammenfassung

Erste Erfahrungen mit der Windkraftanlage MoWEC1 und ihr möglicher Einsatz an der Nordwestküste Ägyptens zur Obstbaumbewässerung mit einem Niederdruck-Bubbler-Bewässerungssystem

Eine neue mobile Windkraftanlage, genannt MoWEC1, wurde mit zwei gegenläufigen Dreiblatt-Rotoren ausgerüstet. Jeder der beiden Rotoren hatte einen Durchmesser von 7,10 m. Im Feldversuch konnte die erste Leistungskurve dieses MoWEC-Prototyps gemessen werden. Installiert waren ein 10-poliger Dauermagnet-Synchrongenerator, Messeinrichtungen für Spannung und Strom, Heizelemente als Verbraucher und ein Dreischalen-Anemometer für die Bestimmung der aktuellen Windgeschwindigkeit. Die Messwerte ergaben einen Gesamtleistungsbeiwert von $C_{Pt} = 0{,}32$.

Gesucht wurde ferner eine wasser- und energiesparende Bewässerungstechnik, die für eine MoWEC1-Anwendung auf kleinen Obstbaumplantagen empfohlen werden kann. Durch einen Vergleich der vorhandenen Bewässerungsverfahren konnte das Niederdruck-Bubbler-Bewässerungssystem für die Bewässerung von Obstbaumplantagen gewählt werden. Dieses System ermöglicht durch den niedrigen Betriebsdruck einen ökonomischen Einsatz des Wassers. Daher ist auch eine gute Kombination mit erneuerbaren Energien - wie der Windenergie - gegeben. Für die Dimensionierung wurde das Computerprogramm LHBIS verwendet, um einfacher und schneller als auf traditionelle Weise Niederdruck-Bubbler-Bewässerungssysteme entwerfen und berechnen zu können. Mit Hilfe des Programms wurde zusätzlich eine entsprechende Bewässerung für 10 ha an der Nordwestküste von Ägypten berechnet.

Das durchschnittlich im Monat durch MoWEC1 gepumpte Wasser an der N.W.-Küste von Ägypten beträgt 21.111 m^3. Dieser Wert ist ausreichend, um 10 ha Obstbäume, Oliven- oder Zitrusbäume zu bewässern. Wenn nur MoWEC1 zum Pumpen von Wasser verwendet wird, ergibt sich aus den MoWEC1-Daten ein durchschnittlicher Wasserpreis von 3,4 €-Cent/m^3.

Schlüsselworte: Windenergie, Mobile Windkraftanlage, MoWEC1, Bewässerungsverfahren, Niedrigdruck-Bubbler-Bewässerungssystem, Computerprogramm LHBIS, N.W.-Küste von Ägypten

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1 Introduction

The world energy demand is continually increasing due to the increase in the world's population, economic growth, and energy usage. But the world supply of oil is projected to last approximately 50 years at current production rates (Campbell, 1997 and Duncan 1998). Worldwide, the natural gas supply is adequate for about 50 years and coal for about 100 years (Bartlett, 1995 and Youngquist, 1997). These projections, however, are based on current consumption rates and current population numbers.

Renewable energy resources can be defined as energy that is replaced rapidly by natural processes. Renewable energy is beginning to grow out of its initial status and has experienced exponential growth in usage over recent years (Hassan, 2003). Most renewable energy sources are derived from solar radiation, including the direct use of solar energy for heating or electricity generation, and indirect forms such as wind energy, wave energy, hydroelectricity, biomass, energy from wastes, tidal power and geothermal energy. Wind energy is one of the most flexible of all renewable energy resources. It can be used for different purposes such as irrigation, generation of electricity, crop drying, grain grinding and also many other purposes through a wind energy converter system.

Mobile **w**ind **e**nergy **c**onverter (MoWEC1) is the prototype of a special kind of wind energy plant which allows the installation of more than one rotor and which has a chassis for transportation. The latter makes it possible to use this machine seasonally at different locations. The rotational energy of the prototype, which is produced by the two three-bladed rotors, leads on to two positions to a shaft for power take off (PTO) use. A three point fastening, similar to the three point hydraulic hitch on modern tractors is used to connect the desired energy transformer to the PTO, like, e.g., a mechanical water pump, a permanent magnet generator for stand alone use or with grid connection, an air-compressor for energy storage or other suitable equipment. There are lots of different designs in terms of heights, width and rated power possibilities, see Figure 1 and Figure 2. The wings tip height amounts in the present MoWEC1 prototype to 10 meters. The total rotor swept area is 80 m^2, because each of the two rotors has a diameter of 7.10 meters (Irps and Omara, 2003). MoWEC1 was designed with rotors at a downwind position from the stationary central tower and at an upwind position from the rotor towers, see Figure 1. An upwind rotor installation minimized the air disturbance at the blades during tower passing. This also results in less noise, lower blade fatigue, and smoother power output. The downwind blades, on the other hand, allow a free yaw system to be used. MoWEC1 has been used for testing and development at the Institute of Production Engineering and Building Research of the German Federal Agricultural Research Center (FAL) in Braunschweig since the beginning of the year 2002.

Energy costs are more significant than water costs in most countries. Today most irrigation techniques are developed for conditions under which fossil energy plants deliver pump energy every time as needed. In contrast, a wind energy plant in stand alone use converts energy only according to the present wind velocity. So it requires a wind energy driven irrigation system which has an energy store, here a water tank. It is also necessary to choose an irrigation system based on the energy source availability and reliability.

An electrical wind energy system like MoWEC1, working mainly in an adapted irrigation system, can also be used to supply remote regions with electricity for other processes.

The following chapters present the first measured MoWEC1 power curve and the suitable selection, simulation and laboratory test of a water and energy saving irrigation technique which can irrigate small orchard farms in Egypt. Wind velocities were taken from the North-west coast of Egypt.

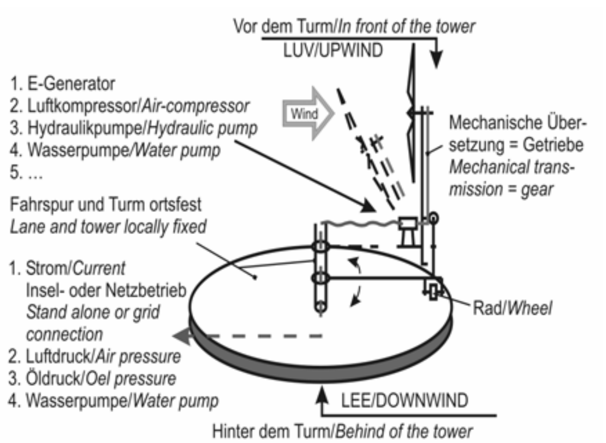

Figure 1:
Construction details of MoWEC1

Figure 2:
MoWEC1 field test

2 Measurement of the MoWEC1 power curve

The power curve for a wind energy conversion system (WECS) indicates the power output from WECS as a function of the wind velocity at hub height. The power curve of a WECS is an important parameter in the wind plant energy yield prediction. More often the power curve measurements are included in the proposed warranty assessment procedures as part of the wind plant commissioning. The power characteristics therefore need to be determined in a proper way.

2.1 Material and method

First power measurements with MoWEC1 were made under stand-alone conditions with a permanent-magnet synchronous generator. The generator current is converted with heating elements into air heat, Figure 3.

The generator fulfills the international safety class system IP 55 (dust and water protected). It is a 10-pole (5 pairs of poles) generator, which achieves a frequency of 50 Hz at the rotational speed of 600 rpm (manufacturer: Hübner, Fabrik elektrischer Maschinen, Giessen, Germany, 2002). During the calibration of this generator in the electric laboratory (see Figure 4), the generator rotational speed, current, voltage, torque and power were measured. The following equations illustrate the generator characteristics. The generator rotational speed as function of the current is according the test:

$$n_g = 43.5\ I_g$$

n_g = generator rotational speed in min^{-1};
I_g = generator output current in A.

The output generator power and torque as a function of the rotational speed are determined with:

$$P_g = 2 * 10^{-5}\ n_g^2 + 0.0034\ n_g$$

and

$$T_g = -9 * 10^{-5}\ n_g^2 + 0.367\ n_g$$

P_g = generator output power in kW;
T_g = generator torque in Nm.

The heating elements are arranged in three parallel phases according to Figure 3. Their technical data are R = 35.2 Ω and P_{max} = 1500 W. The current I on L_1, L_2 or L_3 was measured with a calibrated current clamp. The wind speeds are measured using a digital three-cup anemometer. This anemometer was fixed on a vertical shaft at the MoWEC1 hub height.

MoWEC1 was installed in the field at the FAL experimental station in Braunschweig, Germany, and tested to determine the power curve and the total power coefficient C_{pt}. The wind speed was measured every five seconds. And at each wind speed time, the electric current output from the generator was also measured. Data are taken

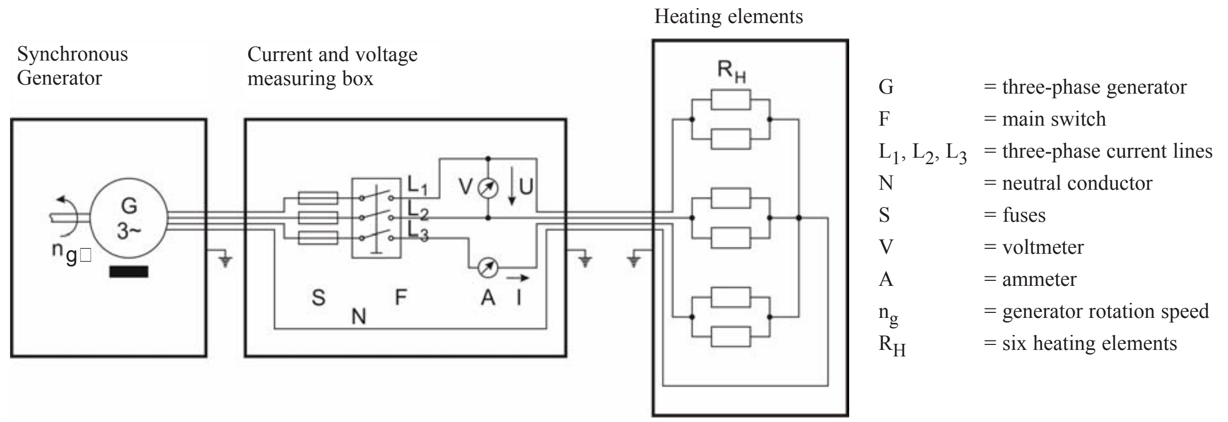

Figure 3:
Electric circuit diagram (Generator and electrical consumer in star-connection)

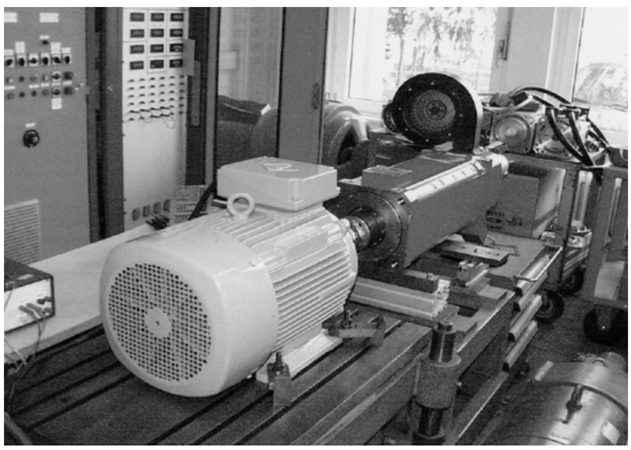

Figure 4:
MoWEC-Generator. Measurement of the electric parameters

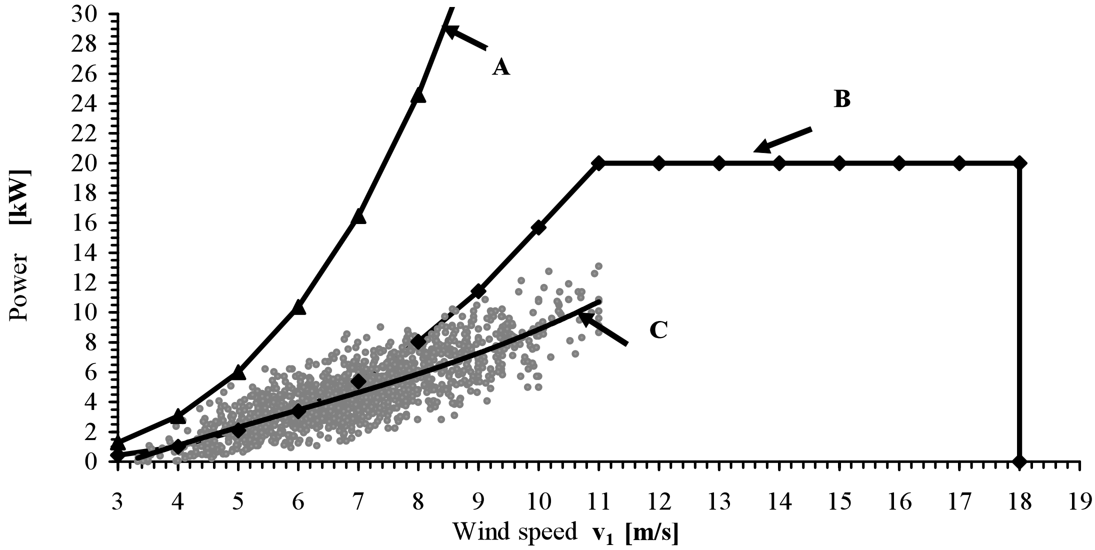

Figure 5:
MoWEC1 power curve: A = wind power; B = extrapolated MoWEC1 power curve with 2 rotors and total C_{pt} = 0.32;
C = measured MoWEC1 power curve

when winds are available, so a test may be a few minutes long or extend to more than an hour. These tests were performed on a day-to-day basis; the final result was a large amount of data taken for a wide range of wind conditions over many days. These data for a given generator output current can be combined with the generator performance equations and so the performance of the MoWEC1 prototype could be computed.

2.2 Results and discussion

2.2.1 MoWEC1 power curve

The first MoWEC1 prototype power curve was measured in a field test with a permanent-magnet synchronous generator, which reaches 9.0 kW/400 V by 540 rpm and 10.6 kW/50 Hz by 600 rpm. A speed of 600 rpm has had a power output of 13.66 kW. MoWEC1 has two rotors (each 10 kW). Therefore we could measure the power curve only until the rated power of the installed generator.

Figure 5 shows three power curves in relation to the wind velocity. First the wind power, second the extrapolated MoWEC1 power with the total average power coefficient of C_{pt} = 0.32, and third the measured power curve. The stall rotor diameter was 7.10 m each and the hub heights 6.45 m.

2.2.2 MoWEC1 actual mean monthly energy production on N.W. coast of Egypt

MoWEC1 power curve measurements are used as input for wind plant energy yield predictions in order to compute the MoWEC1 energy production on the North-west coast of Egypt. Egypt is located in the north-eastern corner of the African continent. The N.-W. coast of Egypt extends about 550 km from Alexandria to Al-Salloum, and about 10-20 km south of the Mediterranean coast.

The daily average wind speed and duration at the N.W. coast of Egypt (stations Alexandria and Mersa Matruh), in the years 1984 to 2002, with wind speeds between 3.5 and 20 m/s were taken to calculate the mean wind speed and duration, see Table 1 (according NWSTOC, 2002).

MoWEC1's actual mean monthly energy production was calculated by using the mean monthly wind speed and duration on the N.W. coast of Egypt, MoWEC1 rotors swept area 80 m^2, air density 1.225 kg/m^3, the MoWEC1 total power coefficient of 0.32 and the Energy Pattern Factor of 2 (Fraenkel, 1993). Table 1 shows the actual mean

Table 1:
Mean monthly MoWEC1 energy production on the N.W. coast of Egypt

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
MWS [m/s]	5.62	5.56	5.82	5.61	5.41	5.51	5.32	5.32	5.19	5.10	5.26	5.75	-
MWD [h/month]	384	388	470	451	469	475	504	496	429	429	383	411	5286
AMEP [kWh/month]	3132	2091	2906	2494	2326	2485	2377	2340	1879	1779	1748	2447	27005

monthly energy production (AMEP) from MoWEC1. Where MWS is the mean monthly wind speed in m/s, MWD is the mean monthly wind speed duration in h/month. Table 1 also contains the actual mean annual energy production (AMAEP) by MoWEC1 in total 27.005 kWh/year.

The total initial investment of the MoWEC1 prototype was 26.000 €, with an additional 4.000 € for the generator and water pump. A payback period of 10 years was selected with an annual rate of interest of 8 %, which results in a fixed charged rate of 14 %. Annual operation and maintenance was assumed to be 2 % of the initial cost, which is 600 €. An actual mean annual energy production of 27.005 kWh/year on the N.W. coast of Egypt was taken (Table 1) for the calculation. The cost of energy with the preceding data was calculated based on the Rampler-Equation (1979) with 17.77 €-Cent/kWh.

3 Wind powered irrigation system

3.1 Selection of an irrigation technique

Irrigation systems fall into three categories: surface irrigation, micro irrigation and sprinkler irrigation, see Figure 6.

Every irrigation system requires a special energy supply. We chose a water and energy saving irrigation technique suitable for a MoWEC1 application on small orchard farms. According to the comparison of the irrigation methods and the characteristic data, the micro irrigation technique is suitable for wind energy or photovoltaic application for sparsely planted crops, like orchards or vineyards. Any other methods (sprinkling) of irrigation either require too-high operating pressures or are unsuitable for small farms because the size of the machines or the output per unit area. Also the surface irrigation has lower application efficiency and it cannot work automatically.

Micro-irrigation is the broad classification of frequent, low volume, low-pressure application of water on or beneath the soil surface by drippers, drip emitters, spaghetti tube, subsurface or surface drip tube, low-head bubblers, and spray or mini sprinkler systems.

Low-head bubbler irrigation enables the economical use of water, and its low operating pressure makes it particularly well-suited for combination with alternative energy such as wind energy water pumping systems. This irrigation system is particularly well suited for orchard crops and requires very low-pressure heads to distribute irrigation water to the trees. It is based on gravity flow and has large orifice opening to deliver water directly to the root zone, thus eliminating the elaborate filtration systems and pumps required by other micro irrigation systems. Despite these advantages, bubbler systems have not been widely used.

3.2 Low-head bubbler irrigation system (LHBIS) model

The computer program LHBIS was written to make low-head bubbler irrigation design simpler and faster than the traditional way of using charts and calculators. It allows a user to determine the distributor hose's outlet elevation or distributor hose's length, and required pressure head at constant head device for a given discharge per tree and field condition. Figure 7 shows the data flow diagram of the computer program.

3.3 Laboratory tests

Laboratory experiments were conducted to validate the LHBIS computer program at three lateral slopes (level, uphill and downhill) by measuring the hose's flow rate, the pressure heads upstream and downstream of each hose inlet. Figure 8 shows the irrigation experiments plant to verify the computer program. The lateral diameter and distributor hose diameter were 32 and 6 mm, respectively. The distributor hoses spacing and length were 4 and 2.5

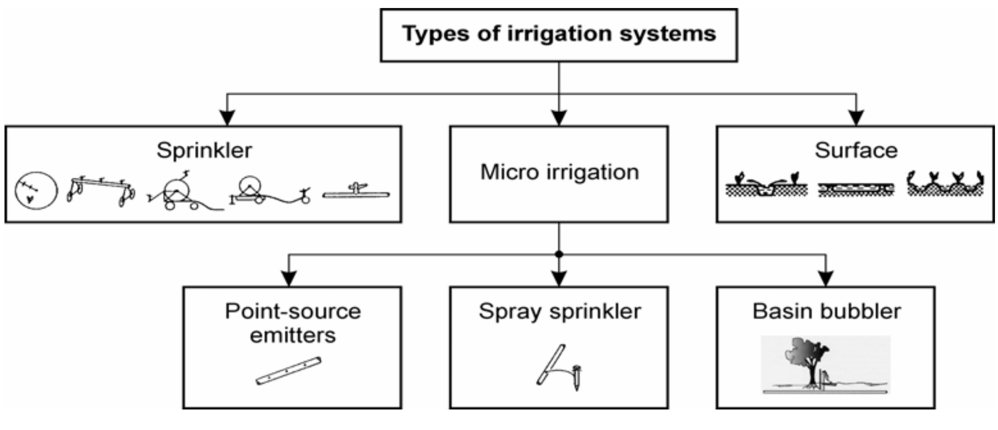

Figure 6:
Irrigation systems (Omara, 2004a and Sourell, 1998)

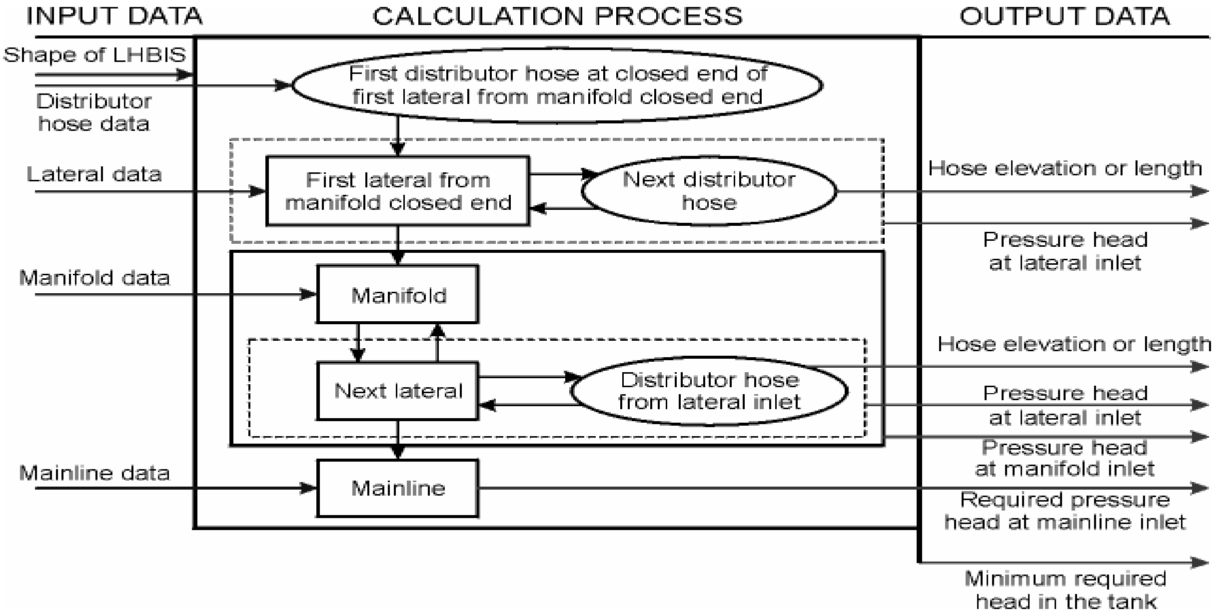

Figure 7:
Data flow diagram of the computer program

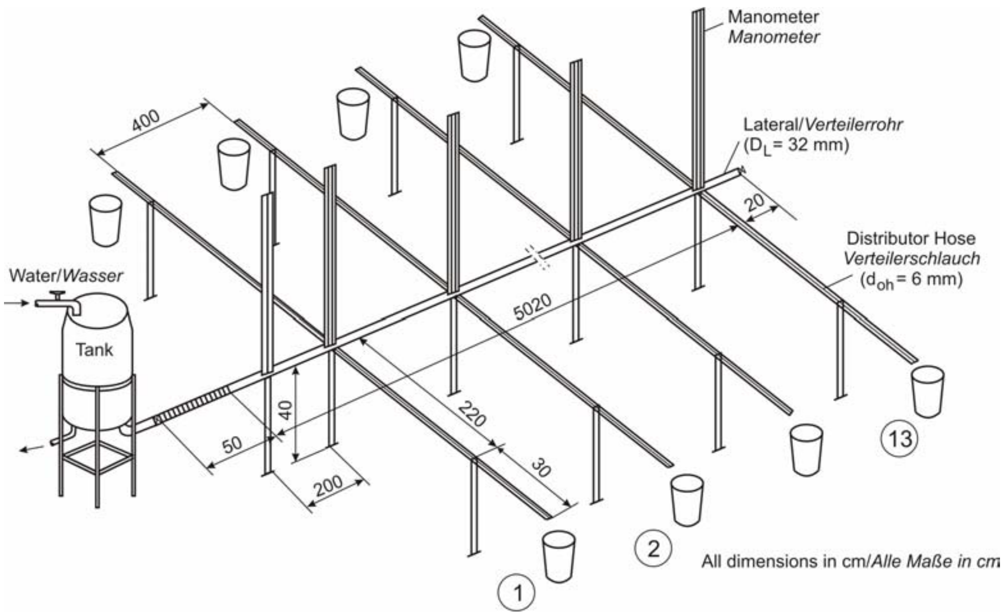

Figure 8:
Irrigation experiments in especial laboratory as a basis to verify the computer program

m, respectively, and number of the distributor hoses per lateral side were 13. The experimental work was conducted in the irrigation laboratory at the Institute of Production Engineering and Building Research, Federal Agricultural Research Centre (FAL), Braunschweig, Germany.

3.4 Results and discussion

The distributor hose's elevation (or length) and required pressure head at lateral inlet were calculated by the computer program. These data were applied in a laboratory experimental system at three lateral slopes and three hoses discharged in two cases. Firstly, the laterals were located on two manifold sides. Secondly, the laterals were located only on one manifold side.

Figure 9 shows the mean measuring and theoretical distributor hose's outflow along one lateral with different distributor hose's outlet elevation. Figure 10 shows the measured pressure head just before distributor hose's and calculated distributor hose's outlet elevation along one later-

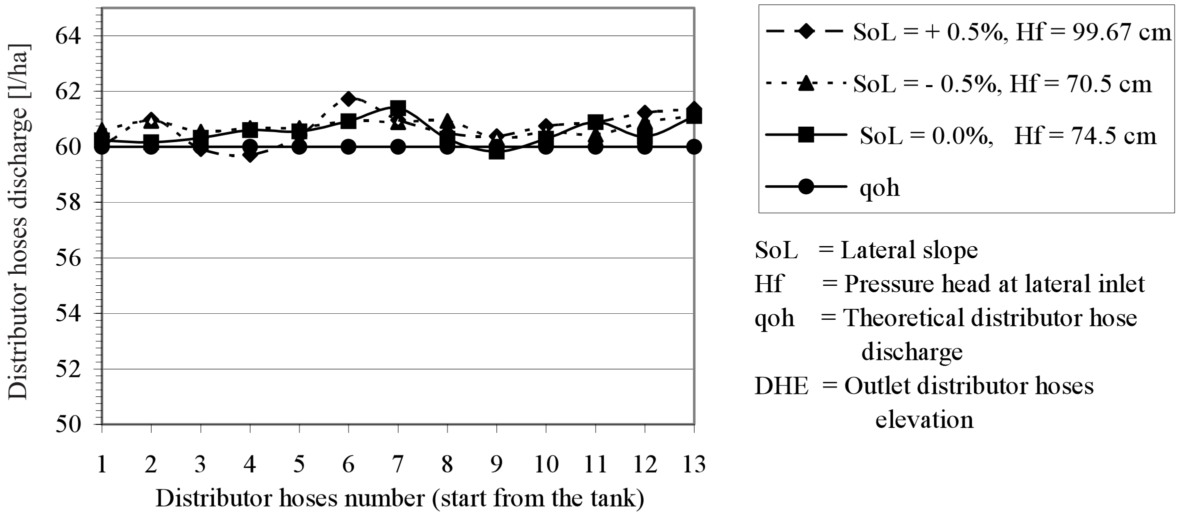

Figure 9:
Mean measuring and theoretical distributor hoses outflow along one lateral with different distributor hoses outlet elevation

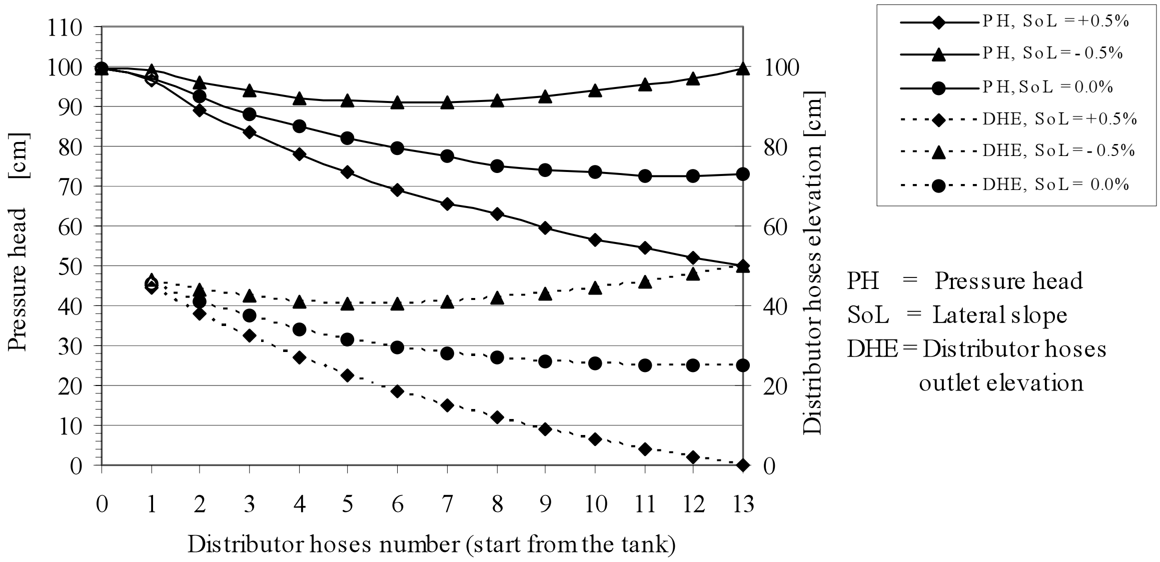

Figure 10:
Measured pressure head just before distributor hoses and calculated distributor hoses outlet elevation along one lateral

al, both figures based on one lateral, the laterals on both manifold sides, and the distributor hoses on two lateral sides. Hazen-William's coefficients of the lateral and distributor hoses were 140 and 115, respectively, longitudinal slope of the lateral pipeline was 0.0 %, + 0.5 % or - 0.5 % and the distributor hose's theoretical discharge was 60 l/h.

The distributor hose's emission uniformity and flow variation were calculated from the laboratory experiments data in two cases when low-head bubbler irrigation system was designed with different distributor hoses elevation or with different distributor hoses length along one lateral. The emission uniformity (EU) values were higher than 97 % at all distributor hose's discharges. On the other hand, the flow variation values were 5 % to 7 %. Keller and Karmeli (1974) recommended that EU values of 94 % or more are desirable, and in no case should the designed EU be below 90 %.

Through running the computer program and laboratory experimental of low-head bubbler irrigation systems with different distributor hose outlet elevations or with different distributor hose lengths, we can recommend the use of irrigation system with different distributor hoses outlet elevation. These are more practical than the system with different hose lengths for irrigating tree crops, especially orchards.

The computer program was used to investigate certain factors influencing the distributor hose's elevation along the laterals and the required pressure head at each manifold inlet of the irrigation system. The results of analysis of a large range of bubbler irrigation systems indicate that the minimum distributor hose elevation is achieved with a small lateral downhill slope of - 0.5 %. The hose's elevation can be decreased by using moderate hose discharge of 40 to 60 l/h, short laterals with small number of hoses ≤ 13 hose per lateral side, large lateral diameter ≥ 32 mm, large manifold diameter ≥ 75 mm and small number of the lateral ≤ 9 lateral per manifold side. The hose's diameter doesn't effect the hose's elevation, but it has a large effect on the required pressure head of the irrigation system. The pressure head achieved increases rapidly as hoses diameters decrease < 4 mm. Hoses with a diameter of more than 8 mm have only a small affect on the required pressure head at manifold inlet (Reynolds, 1995).

4 MoWEC1 water pumping for bubbler irrigation system at N.W. coast of Egypt

Irrigation is one of the main energy consumers in agriculture. The combination of a wind-electric system with suitable irrigation equipment for the watering of fruit trees may also provide electricity for common applications in regions without a public electrical grid. For this study, a low-head bubble irrigation system was chosen because the needed water tank allows the transformed potential water energy to be stored. In addition, this irrigation system enabled the economical use of water, and its low operating pressure makes it particularly well-suited for combination with alternative energy such as wind energy.

Ground water is adequate and accessible along most parts of the N.W. coast of Egypt at a depth ranging from 5 to 50 m (Balba, 1981 and El-Mallah, 1991). A report by UNDP/FAO (1970) indicated that an area of 137,460 ha in this region is suitable for fruit trees.

If the total orchard field area is approximately 10 ha, the field shall be divided into four large plots; each plot has an area of $100 * 250$ m^2, see Figure 11. The water storage tank will be constructed individually for each plot at the middle of the area. In a wind-energy water storage tank system, water is pumped year-around into a storage tank by an electric or mechanical wind-powered water pumping system. The tank and the wind plant are sized so that the crop's water needs are met throughout the year. In this paper it is assumed that the water source is shallow groundwater with a sum of well-depth and draw down of about 12 m, and the total required dynamic head for the pump was calculated to be 24 m by the computer programme. The water level in the tank may be not constant at all operation times, in this case a constant head device must be used to obtain the manifold constant design pressure head at all operation times. Figure 12 displays a layout of the orchard low-head bubbler irrigation system.

The amount of water needed by the crop depends on the rate of water transpired by the plants and the evaporation rate from the soil surface. The maximum monthly irrigation requirements for 10 ha orchards, olives or citrus trees at the N.W. coast of Egypt were found in July; they amount to 16,648, 18,093 or 23,784 m^3/(10 ha $*$ month), respectively. Figure 13 shows the mean monthly irrigation requirement (MIR) for orchards, olives or citrus trees and water (Q_M) pumped from MoWEC on the N.W. coast of Egypt.

The average mean monthly MoWEC1 water pumped at the N.W. coast of Egypt is 21,111 m^3/month when the total dynamic head is 24 m. If MoWEC1 is used only for pumping the water to irrigate 10 ha of orchards, olives or citrus trees at the N.W. coast of Egypt, the cost per each one m^3 of the water with 24 m total dynamic head would be 2.77, 3.92 or 3.5 €-Cent/m^3 of water for orchards, olives or citrus, respectively. These data are based on the economics of the MoWEC1-prototype.

5 Summary and conclusion

Renewable energy is beginning to grow out of its initial status and has experienced exponential growth in usage over recent years. The combination of a wind-electric system with suitable irrigation equipment for the watering of fruit trees may also provide electricity for common applications in regions without a public electrical grid.

MoWEC1 is the prototype of a special kind of wind energy plant. It was designed with two three-blade rotors running in opposite directions and with a yaw drive, which has its travel path on a locally fixed portable frame. The wing tip heights amount in the MoWEC1 prototype to 10 meters. The total rotor swept area results in 80 m^2, because each of the two rotors has a diameter of 7,10 meters. The first power curve of the MoWEC1 was measured in a field test with a permanent-magnet synchronous generator. The MoWEC1 total average power coefficient was calculated from the power curve with 0.32. The actual mean annual energy production by MoWEC1 on the North-west coast of Egypt was calculated to 27,005 kWh/year. The total initial cost of the MoWEC1-prototype was 30,000 €. The cost of energy was calculated with 17.77 €-Cent/kWh.

As application water and energy saving irrigation technique suitable for a MoWEC1 application a small orchard farms was chosen. According to the comparison of the irrigation techniques, the low-head bubbler irrigation enables the economical use of water, and its low operating pressure makes it particularly well-suited for combination with alternative energy such as wind energy water pumping systems. The design of this irrigation system is very important, so the computer program LHBIS was written to make low-head bubbler irrigation design simpler and faster than using charts and calculators. Laboratory experiments were conducted for the validation of this computer program at three lateral slopes.

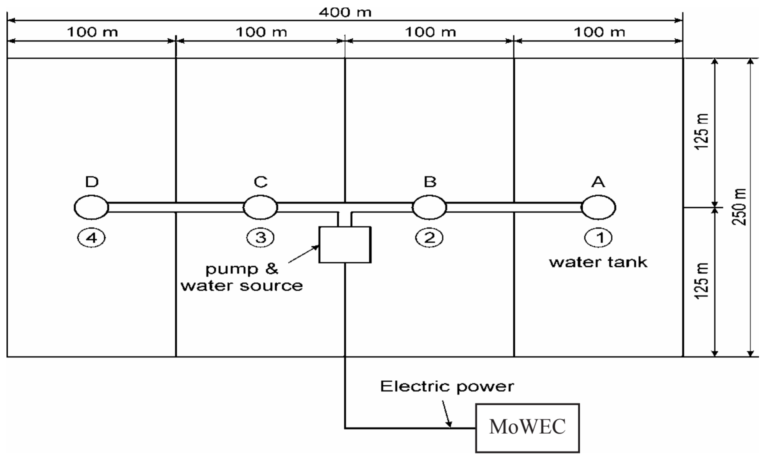

Figure 11:
Layout of the irrigation field (Omara, 2004b)

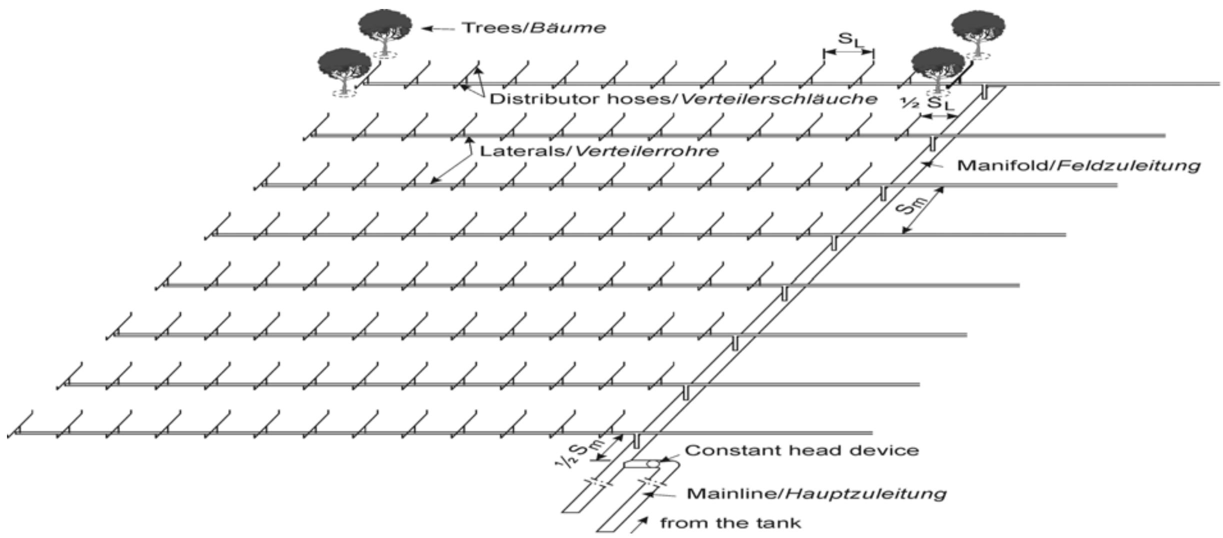

Figure 12:
Layout of the orchard low-head bubbler irrigation system (Omara, 2004a)

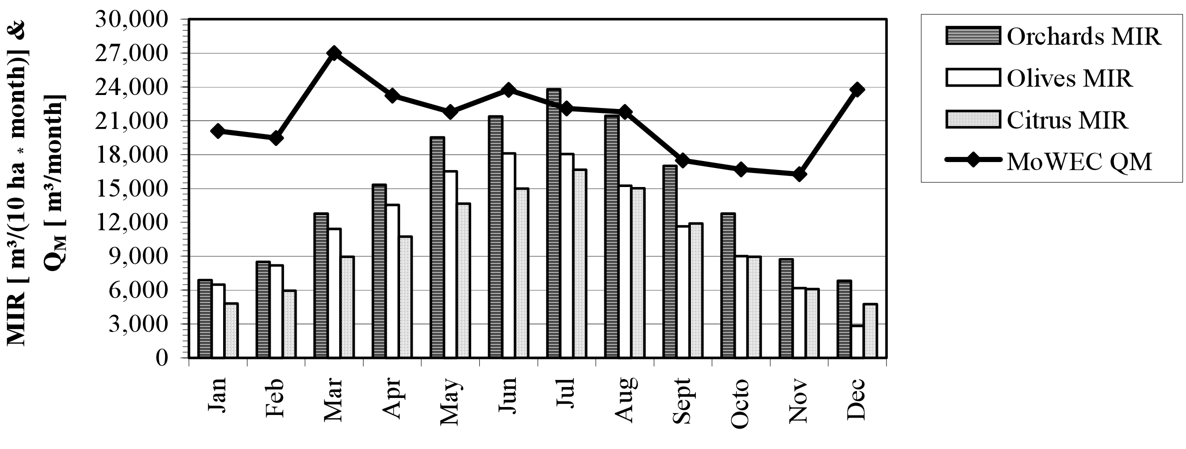

Figure 13:
Mean monthly irrigation requirement (MIR) and pumped MoWEC water (Q_M) at the N.W. coast of Egypt (Omara, 2004c)

The computer program was used to design the low-head bubbler irrigation system for 10 ha at the N.W. coast of Egypt. The maximum monthly irrigation requirements for 10 ha orchards, olives or citrus trees at the N.W. coast of Egypt were found in July; they amount to 16,648, 18,093 or 23,784 m^3/(10 ha $*$ month), respectively.

The average mean monthly MoWEC1 water pumped at the N.W. coast of Egypt was calculated with 21,111 m^3/month, when the total dynamic head is 24 m as calculated by the computer programme. If MoWEC1 is used only for pumping the water to irrigate 10 ha at N.W. coast of Egypt, the cost per each m^3 of the water would be 2.77, 3.92 or 3.5 €-Cent/m^3 of water for orchards, olives or citrus respectively, based on the economics of the MoWEC1-prototype.

In the future, the wind-electrical system MoWEC1 can be used in a versatile manner. The described combination with water and energy-saving irrigation system (low-head bubbler irrigation system) for fruit trees and orchards is only one targeted application. Generally, electricity in the stand alone plant can be made available everywhere with sufficient wind velocities, where no utility supplied electricity or where fossil energy is particularly expensive. Thus world-wide a small contribution can be made for the reduction of the water and energy shortage over MoWEC1 and this new irrigation system.

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