About two billion people do not yet have a sufficient electricity supply. While this applies to many rural areas in developing countries, up to two million people in Europe live far from supply lines, mostly on small islands, or in inaccessible mountain regions. Here, electrification often begins with individual, decentralised stand-alone systems which depend on diesel generators. While earlier attempts to realise a basic supply involved many small systems which were only extendible to a limited degree, ever more stand-alone AC grids with new possibilities are now being designed. Electricity generated in a decentralised manner from diesel generators, photovoltaics, hydropower and also from wind energy, is fed into the grid at arbitrary locations. The stand-alone grids can be expanded and interconnected according to demand and available finances. In recent years, intensive research has been conducted for the development of modular system technology and its components, for hybrid systems such as these.

In a research project sponsored by the German Federal Ministry for the Environment, a small wind turbine has been developed, with a rated output of 5 kW, which can be implemented in stand-alone operation, as well as parallel to the grid. A lightweight structure, high availability, long maintenance intervals, and optimised energy yield should keep the operating costs low and also enable implementation in remote grids, even with unfavourable climate conditions. The developers are aiming to achieve a series price of around €1,000/kW (without tower), i.e. a sum similar to those typical of large systems today. To this end, all components of the wind turbine have been tested for possible savings and improvements. Primarily, optimisation possibilities are being researched for the rotor blades and the generator, as these are components which are often disproportionately expensive for small systems.
Supply and demand

It is relatively easy to identify countries which have an insufficient electricity supply. However, the locations where wind-based decentralised energy systems have actual market potential are determined by numerous factors, such as infrastructure, climate, financing, etc. The worldwide possibilities for decentralised electricity supply with small autonomous systems have been investigated in a comprehensive market analysis. The central objective was to determine which countries are suitable for implementation of the planned 5 kW wind turbine. It was determined that at present, the greatest market potential is in the USA, India, Australia, Great Britain and China. In this analysis, not only the population situation, the gross domestic product, and the wind conditions were taken into account, but also the extent to which these countries already have structures available for the marketing of small wind power systems, and for implementation of decentralised energy supply projects. Many small wind turbines are available in the output range of a few kilowatts, and are mostly manufactured in small numbers. The size-specific prices of these small systems are in some cases double, or even triple, those of today’s large wind power systems. In many cases, their electrical equipment is not intended for direct connection to modern hybrid systems for decentralised supply.

System design: less is more

Achieving maximum reliability with minimum maintenance requirements is a particular challenge. To this end, fault-susceptible mechanical functional units in the wind turbine are being reduced, or replaced with electrical components. Being a self-tracking downwind machine, the system does away with active control elements for wind tracking. With a special rotor concept, it is also possible to do away with a controller which turns the rotor out of the wind in extreme wind conditions. All system components must have long-term protection against sand and dust penetration, and against corrosion caused by damp air with high salt content. Also, the nacelle weight should allow transport and installation of the system with simple equipment. The structure and manufacture of all components have been examined for possible savings and simplifications with optimised efficiency. This applies especially to the rotor blades and generators, as these are often disproportionately expensive in small systems.

Those who are cleverer give in – the rotor

The turbine’s three rotor blades are manufactured economically from extruded glass fibre reinforced plastic (GRP) sections (fig. 3). This material has good fatigue properties, high resistance to abrasion, and excellent UV-resistance. The blade sections are designed so that the power output at high wind speeds is limited by the stall effect. Despite a simple blade design, with constant depth and no twist, the rotor achieves high efficiency (cp = 0.43).

The wind turbine survives wind speeds of up to 65 m/s. This equates to very heavy weather conditions, far beyond hurricane wind speeds. This is achieved due to the rotor blades’ low bending stiffness in the direction of impact. Thus, in extreme winds of 65 m/s, the rotor radius decreases to 67%. At the same time, the bending reduces the drag coefficient. In extreme wind conditions, the combination of these two effects halves the wind stress on the entire system in comparison to systems with rigid blades. This allows savings on material for the load transfer components, such as rotor shaft, machine housing, vertical bearing, tower, guys and foundation, thus reducing the system’s manufacturing costs considerably.

Well adapted – the generator

The rotor is coupled to an asynchronous generator by means of a single-level spur gear unit. The pole-switchable generator is switched between two rotational speeds, according to the present amount of power being fed. On the first level, the rated output is 1.5 kW, and it is 5.5 kW on the second level. On the high rotational speed level, the generator achieves high partial load and maximum efficiencies of up to around 90% with a power output of 3 kW (fig. 4). Also at the low rotational speed, the maximum efficiency is 84% with a power output of about 1 kW. The high efficiencies when outputs are low suit the design of a wind power system very well, as such systems’ largest contributions to the energy yield result from medium wind speeds. Somewhat lower efficiencies at rated output cause a comparatively slight reduction of the overall energy yield. The developers have gone to great lengths to reduce the air gap between rotor and stator. This has a decisive influence on the generator’s power factor, and thus on the generator’s reactive power, which must be provided by other components in the grid. The technically realisable reduction of the air gap to just 0.25 mm improved the power factor in the partial load range by 10%. Simultaneously, the efficiency in the partial load range also increased by about 10%.

Flexible – the operational management

This wind turbine is designed for different electrical grid conditions. It can be operated parallel to the grid, and also in a stand-alone grid, in conjunction with a battery inverter. As well as the model with a 3-phase generator (400 V / 50 Hz), a version with a single-phase generator (240 V / 60 Hz) is envisaged for operation in the USA. The opera-
tional management unit is accommodated in a separate stainless steel housing with protection degree IP65, and is fastened to the tower below. It has a data interface, via which the measurement data can be collected and/or parameters can be set. Remote monitoring is possible via a telephone line or GSM modem.

In addition, for incorporation into the hybrid system, an adjustable load has been developed, with which excess energy in a stand-alone grid can be discharged systematically. The operational management unit has the task of detecting all of the system’s operating states, and initiating appropriate reactions. A chain of sensors monitor operations to ensure that system operation is secure. This safety chain comprises an overspeed switch, a vibration sensor, and a temperature sensor.

### Connected to the grid, and autonomous – prototypes put to the test

The first two prototypes were initially tested on a test stand at the University of Kassel (fig. 6). Here, the dynamics of the wind were simulated by a motor which was flanged to the generator. It was primarily the examination of voltages and currents upon connection of the generator to the stand-alone grid via the newly developed operational management unit which yielded many findings, which it was possible to incorporate into the first versions of the operational management unit.

#### Connected to the grid

A prototype, optimised on the test stand, was installed in Spring 2004, at the Windtest Kaiser-Wilhelm-Koog GmbH test field. This system is connected parallel to the grid, and has been in fully automatic operation since late summer 2004. After it confirmed its general suitability, and achieved the envisaged rated output at high wind speeds, comprehensive optimisation work began. For instance, the start-up behaviour, automatic connection to (and disconnection from) the grid, and switching between the generator levels were examined. The alignment of the nacelle in relation to the wind direction was also analysed. If the nacelle were to oscillate significantly, and if it were often aslant to the wind, it would not be possible to utilise a portion of the potentially available energy, and the tower could be caused to sway in an undesired manner. The measurements showed good, stable yawing. Based on the measurements, it was possible to significantly improve the system concept and the components. For instance, the analysis of two different rotor blade incidence angles shows how sensitively the power output reacts to the incidence angle (fig. 7). For optimisation of the first blade sections, which were developed with the aid of computers, the intended incidence angle had to be corrected by just 1° in order to optimise the power output.

#### and autonomous

The second prototype is being tested while operating with an autonomous hybrid system. The test field ‘Alte Schanze’ near Kassel, Germany, is about 400 m above sea level. The terrain and vegetation provide typical inland wind conditions, with relatively low wind speeds and high turbulence on average, in comparison to the coast. The hybrid system (fig. 8), with a 2.6 kW photovoltaic system as well as the wind turbine, is operated autonomously, without grid connection. A diesel generator serves as backup. If a large amount of electricity is being fed in by the photovoltaic system and the wind power system when the battery is already charged, a thermal resistor can increase the consumer power significantly. The core of the experimental hybrid system is composed of three battery inverters (4.5 kW), which form the grid and monitor it in conjunction with the battery bank (60 V, 30 kWh). All other components connected to the grid (3 PV converters with 850 W each, 9 kW diesel generator) also feed into the stand-alone grid, in addition to the wind turbine.

The primary subject of investigation is the interaction between the prototype and the battery inverters. Voltages, currents, and the frequency are observed in the various operating states and in particular during connection to the grid, and upon switching between the two generator levels. The wind turbine itself is also examined, including, for instance, the effects of the tower’s shadow on the rotor torque and output, stimulation of tower oscillation and blade oscillation, or the effectiveness of the stall effect for limitation of output.
**Outlook**

The results from the test fields ‘Kaiser-Wilhelm-Koog’ and ‘Alte Schanze’ are so encouraging, that a pre-production series is to be tested in real operating conditions. At present, ten systems from the pre-production series are being installed at worldwide locations which offer extreme weather conditions: high wind speeds, extreme temperature differences, moisture, dust, and air with salt content.

For the ten systems, the following locations were selected from a large number of candidate sites after intensive testing:

- Greece, Mount Athos (operation in a stand-alone grid)
- Madagascar, Sahasifotra (operation in a stand-alone grid)
- France, La Baume de Transit (grid-parallel operation)
- Ireland, Cape Clear (grid-parallel operation)
- Germany, Großschirma, Ore Mountains (operation in a stand-alone grid)
- Germany, Göttingen (operation in a stand-alone grid)
- Spain, Tenerife (grid-parallel operation)

At present, it is envisaged that the test operation shall last approximately one year. The experience gathered at these sites will be incorporated into the final system design. Under the name ‘aerolSmart5’, the first series-produced systems should be delivered in mid-2008.

The wind turbine’s rated output is suited to the typical low power levels of generators and consumers in decentralised supply systems. If consumer power levels are somewhat higher, the modular philosophy of the hybrid system enables easy integration of several wind power systems in parallel. In such situations, a 10 kW wind power system would probably be considerably more economical than two 5 kW systems. Therefore, possibilities are to be investigated for development of a 10 kW variant, on the basis of the wind turbine which is currently being tested.