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Universität Stuttgart

SWE

10 years Endowed Chair - Wind Energy

Review and outlook

0 Foreword by Karl Schlecht

In 1957, as a young mechanical engineering student at the Technical University of Stuttgart, I took part in an excursion. We visited Ulrich Hutter, then already quite a famous engineer and university lecturer, in his workshop on the edge of a glider landing field in Nabern an der Teck. There, in a wooden barracks that still stands today, he was laminating the blades for a wind turbine made of fiberglass. At the time, this was a revolutionary material that was being used for the first time in the construction of gliders. The material fascinated me immensely; I was eventually a glider pilot myself, and later a sailor and windsurfer. Head: Everything that has to do with the wind.

I found and still find extremely exciting. The complexity of the work that Hutter carried out was impressive. In that hour, Hutter had infected me with the wind power virus.

Foreword
from Karl Schlecht

After graduating, I dedicated myself to building a Mortel pump and became an entrepreneur. My small company grew into a global corporation called Putzmeister, with 4,000 employees and billions in sales. We exported machines all over the world and built numerous plants abroad. The scientifically oriented art of engineering that we practice has enabled us to build record-breaking structures, such as the iconic 800-meter-high Burj Kalifa in Dubai.

In 1998, I contributed my entire company to the non-profit Karl Schlecht Foundation (KSG). All the Putzmeister shares there were also sold in the interest of KSG to **SANY**, a private construction machinery manufacturer from China, which is committed to the same humane and entrepreneurial values as KSG. Today, the independent company - the former garage company Putzmeister - continues to be a global market and technology leader in the segment of concrete pumps and plastering machines. There's no question about it: I've had a lot of luck in life. But it was also always a hard struggle.

Once, I think it was in 1997, I was hiking in the Schwabische Alb, I saw a wind turbine towering into the sky. It stood on the venerable wind power test field ,,Ulrich. W. Hutter". At the sight of the weilsen wings circling in the wind, I remembered the meeting with Ulrich Hutter. At that moment, the desire grew in me to get involved in wind energy myself. Finally, I saw a great future in the use of wind power. I bought three wind turbines in the Sudschwarzwald. I quickly realized that the technology was still immature, that there was still a lot of research to be done.

I decided to endow a chair for wind energy at "my university" in Stuttgart in order to give the still young field of wind energy a scientific and academic home. This was not so easy at first: at that time, Baden-Wurttemberg was governed by the CDU, and thus not exactly wind power-friendly. But the tireless commitment and persuasive work of Heiner Dorner, who had long been Ulrich Hutter's companion and deputy at the University of Stuttgart, gave my project a boost and ultimately convinced me to go ahead.

Foreword
from Karl Schlecht

all critics. After Hutter's retirement from 1980 to 2004, Dorner had taught wind energy to a number of students at the Institute of Aircraft Design and had taken numerous examinations. He had supervised several diploma theses on wind energy. Dorner was the one who kept the wind flag flying at the University of Stuttgart the whole time. The plan to establish the chair became perfect when we were able to win Professor Dr. Martin Kuhn, a proven wind power specialist, as the holder of the first wind energy chair in Germany. And so the first semester at SWE began in 2004. The chair and the courses offered were quickly well received by the students.

Today, the University of Stuttgart and the Faculty of Aeronautics and Astronautics consider the Wind Energy Chair not only an enrichment and a continuation of their wind energy tradition, but of research and teaching on the energy transition in general. In the meantime, over a thousand students have been trained at SWE. Over a hundred diploma theses have been written. Numerous graduates have found excellent jobs in industry or research and helped make wind power what it is today: a global industry that is transforming the energy market. Many graduates are well-known figures in the wind power world and have fond memories of their time in Stuttgart. In the area of research, the chair has been able to build up its own profile and is now a major player in the wind energy world, both among international research institutions and in the industry. In short, SWE enjoys an excellent reputation worldwide.

Today, it fills me with pride that wind turbines are producing more and more electricity all over the world and increasingly replacing fossil fuels. At SWE, the focus is no longer on whether wind energy has a future, but on technical details, on how the wind turbine as a whole can become even more efficient and take over ever greater parts of our electricity supply.

Roof I am also critical. I do not believe in 100 percent renewable energies. I am aware that there are still many details to be solved - both technically and in terms of cost, environmental protection and aesthetics. One of the inevitable pitfalls of expanding renewables is that they make our electricity more expensive. This calls for an interest in saving energy. Roof

Foreword
from Karl Schlecht

It's not just wind power: energy sources are plentiful these days. In the meantime, KSG is funding professorships in various areas of renewable energies, both at the University of Stuttgart and at Reut lingen University.

I am sure that today's wonderful and highly effective wind power plants will take an even greater share of the global energy mix with the help of research work such as that carried out by the Stuttgart Chair of Wind Energy. This requires research and teaching. I know that this task is in good hands with Professor Po Wen Cheng, who has headed SWE since 2011.

Allow me to conclude with a remark: I have only met the "wind pope" Ulrich Hutter a few times. But this one time, in that wooden barracks in Nabern an der Teck, has remained particularly in my memory. When I think of Ulrich Hutter today, I still think of the typical smell of GRP that I associate with my enthusiasm fi.ir wind energy. Hutter remains one of my enriching role models as a persistent and scientifically grounded engineer. He transferred the aerodynamic blade design from gliding to rotor blade construction and replaced the previous sheet metal or flat blades. These decisive features and the three-blade design are now the industry standard. In this respect, Stuttgart can justifiably be called the cradle of modern wind power. I am very pleased about this.

I thank all who have helped make the chair what it is today and wish that it will continue to be an example for talented and inspiring students.

Karl Schlecht, August 31, 2017

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Introducti
on

Professor Cheng,
Professor h.c. Schlecht,
Professor KUhn

Dear Readers,

It was a dream come true". Martin Kuhn, the first chair holder of the Stuttgart Chair of Wind Energy, responded with this sentence when he learned that he would be the first wind energy professor in Germany. Martin Kuhn led the chair from its inception in 2004 until 2010 and was a key figure in shaping it.

Some people might be surprised that Stuttgart, of all places, the automobile city, should be a top address on the international map of wind power. But rest assured: Stuttgart is indeed a hotspot for wind power development. And it has been from the beginnings of modern wind energy use to the present day.

That's why we want to use this book to trace the history of wind power in general, but also to look specifically at the contribution made by the people of Stuttgart. We want to give you a sense of how much Stuttgart has contributed to the global success of wind power, and to show you what the future will bring.

The fact that wind energy arrived at the University of Stuttgart at all is primarily due to the work of the Austrian-German engineer and university lecturer Ulrich W. Hutter. In 1944, he was appointed to teach fluid mechanics and flight mechanics at the Technical University of Stuttgart - and had the use of wind energy in mind. Hutter came up with numerous wind power innovations that are still the global standard today, such as the production of rotor blades with fiberglass-reinforced plastics or the blade loop connection. As early as the 1970s, the German Aerospace Center (DLR), which is still located in the immediate vicinity of the university in Stuttgart-Vaihingen, played a central role in the development of wind turbines. Hutter maintained close ties with this research center, which was then called DVLR.

When Hutter retired from his position at the University of Stuttgart at the end of the 1980s, wind energy research in Vaihingen became very quiet. Heiner Dorner, a close confidant of Hutter's who accompanied him around the globe to conferences and speeches and often represented him, continued to keep the wind power flag flying high - even in the harsh headwind of the CDU government. It is ultimately thanks to Mr. Dorner that the Chair of Wind Energy exists today: Starting in 1968, and intensified after the first energy crisis in 1972, Hutter's knowledge of wind energy was established as a new additional department at the institute. From then on, the 'new' field of work at the IFB (Institut fi.ir Flugzeugbau) ran parallel to the aircraft construction training with lectures and research work. Hutter virtually adopted me into the field of wind energy as his companion and deputy," recalls Heiner Dorner.

And yet another person plays a key role within SWE: Karl Schlecht. Without the commitment of the founder of Putzmeister AG and his love of wind, the SWE would probably never have been founded. He endowed the chair for ten years. In addition, Karl Schlecht has been involved in numerous individual projects with his foundation and continues to do so today.

n the meantime, SWE can boast numerous global successes. Bend-torsion-optimized rotor blades, for example, are a child of the Stuttgart-based wind power specialists. Likewise, the laser measurement method LiDAR and the (so-called pradictive) control of wind turbines with the same is now a globally recognized and respected technology. Curiously, Stuttgart, of all places, is synonymous with floating wind turbines in the ocean. But even at SWE, mobility is not completely absent: In the InVentus project, Stuttgart students have been celebrating successes, even world records, for years - they are independently developing a vehicle powered solely by the wind and are taking part in races.

The success speaks for itself: former Stuttgart wind power students and
-Today, students are working in fi.herding positions to advance the wind power industry ever further - thus fi.hering an old Stuttgart tradition.

We wish you, dear readers, an exciting walk through the past, the present and the future of wind energy.

Wenn der Wind der Veränderung weht, bauen die einen Mauern und die anderen Windmühlen.

Chinesisches Sprichwort

Cradle of wind power - how it all began
Technology is evolution

The history of wind power goes back thousands of years. Since windmills not only grind grain, pump water or otherwise do mechanical work, but also supply electricity, their success has been almost unstoppable.

Exactly when and where mankind's first wind turbine turned is not known. However, it is fairly certain that the Persians had the wind working for them more than 2,000 years ago to save them from having to do all the hard work. Their turbines probably consisted of little more than wood and cloth. Today's turbines, on the other hand, are highly complex, computer-controlled and gigantic machines made of high-tech materials. Their task has also changed dramatically: Direct mechanical work is largely a thing of the past; instead, the production of electrical power is the primary goal. And the plants are getting better and better at this. This is proven by their success: They are penetrating the last corners of this earth - from polar regions to deserts and mountains to the vastness of the oceans.

Today, wind turbines with a combined rated output of around 500 gigawatts are in operation worldwide. This is equivalent to the output of around 500 nuclear power plant bli:cks. In some regions, wind power is already the most favorable of all electricity sources. Why should anyone burn fossil fuels and fuel climate change? In combination with storage or as gigantic offshore wind farms, wind turbines can even supply humanity with base-load power and thus replace fossil and nuclear power plants altogether. So far, the evolution of wind power has been extremely successful. But it is far from over.

One after the other. Everybody knows the picture of Dutch

Cradle of wind power
- how it all began
technology is evolution

Windmills. By the thousands, their wings turned from the 16th century, mainly to pump water. In a way, the Holliinder mill provided the blueprint for today's wind turbines. While the rotors of the Persian mills still rotated vertically, the Holliinder mills brought them horizontally. This seemingly small difference is crucial fi.ir the efficiency of the plants. This is because the ancient Persian windmill uses the drag of the sail to generate rotation. This, however, is inefficient, as stri:imation theory spiiter proved. The Holliindi windmill, on the other hand, uses the lift of the sail. This doubled the efficiency compared to the Persian mills. However, towards the end of the 18th century, it became quiet about the
Windfiinger: With the help of the steam engine and spiiter the combustion engine, fossil energy triigers conquered coal
and 01 the world - and verdriingten the beflugelten power plants.

But wind power had not fallen asleep, it was merely dormant. About 100 years later, it reappeared from the depths of oblivion. The public, however, hardly noticed. It was the time of the electric current: The first light bulbs lit up the streets. Electromagnetism was a source of fascination for science. During this time, the Scottish inventor James Blyth developed an electricity-generating wind turbine that is considered the world's first. In July 1887, his turbine converted wind into electricity for the first time. Blyth used it to power lead-acid batteries.
- Even in the evening, when there was a calm, he was not left in the dark, but could work until late at night. In total, ten 25-volt incandescent lamps lit up in "moderate breezes," the inventor wrote.

Exactly what his wind turbine looked like is in dispute. In a letter from May 2, 1888, which Blyth had written to the Philosophical Society of Glasgow, he described it thus: "A tripod, with a rotor about ten meters in size, four struts each four meters long with cotton sails on them, and a Burgin dynamo driven from the flywheel by a rope." Unquestionably a high-tech machine for the time. He wanted the citizens to share in this technological progress: When his batteries were charged, Blyth donated the electricity to the nearby town of Marykirk to light the streets there at night. However, the restrictions were soon removed: Electricity was considered to be the devil's work. For the representatives of the "fossil industry," who were united in the Glasgow Philosophical Society, including steam-engine

Co-inventor James Watt and other Gr615en, electricity was quite simply competition. You can see that: Even then, certain industry representatives were afraid of renewable energies. Today, 130 years later, Blyth's native Scotland is one of the global hotspots of wind energy.

James Blyth recognized early on where the challenges of wind energy utilization lay - namely, taming the mighty forces of the wind. He was the first to quote: Any fool can make a wind turbine go round to generate electricity, but the challenge is to make one that can be left unattended without over-speeding to destruction." The real art, then, is to build a turbine that automatically adapts to wind conditions without being damaged when wind speed increases.

Cradle of wind power - how it all began technology is evolution

In 1891, "electric wind power" reached mainland Europe. The Danish physicist Poul la Cour built a test facility on the Askov school grounds. It was he who first gave the blades an approximately aerodynamic shape and reduced their number to six blades in order to accelerate the speed of rotation of the shaft - more revolutions are good for the electricity yield.

Of course, all the transitions are ongoing. Developments rarely grow from the dung of individual inventors, but rather from the thoughts and attempts of many - technology is evolution. Nevertheless, certain epochs and developments can be attributed to individual persons.

One of these people is Albert Betz. The head of the Aerodynami schen Versuchsanstalt Gi:ittingen was instrumental in formulating the theoretical basis for the use of wind energy. In 1919, Betz formulated a law stating that a maximum of 59.3 percent of the wind's kinetic energy can be used. Betz's law is still valid today - even if creative inventors repeatedly claim to be able to get more than Betz's maximum from the wind.

Inspired by upwind technology and supported by Nazi industrial policy, German inventor and wind energy pioneer Hermann Honnef set out on hi:ihen flights. In the 1930s, he designed wind turbines with a megalomaniac maf5stab: turbines with an output of up to 20 megawatts, up to 500 meters high, and three rotors with 160 meters each.

diameter should carry. However, his giant riders existed only on paper. Even today's megamachines are only half as big, at around ten megawatts.

A real monster plant for its time was built in the USA in 1941: The
Smith Putnam" was the world's first turbine. of the megawatt class. It had a rotor diameter of 53.3 meters and a generator with a rated output of 1.25 megawatts. Its blades, however, were still miles away from those profiled today - they were more reminiscent of boards. The monster was not supposed to live long: in 1945, after one blade was torn off, the turbine was shut down.

At about the same time, what would become today's wind power industry was formed in Denmark around the engineer Johannes Juul. At that time, a number of dedicated tinkerers were tinkering with wind turbines and exchanging ideas. Many of them were farmers who wanted to supply themselves with electricity in the face of rising energy prices. This is how the world-famous "Diinic Concept" came into being: three blades, a gearbox, and an asynchronous generator that feeds directly into the grid. For the first time, the rotor blades were equipped with a stall control system - a system that slows down the blades when there is too much wind by cutting off the current, thus protecting the turbine from destruction.

In Germany, it was primarily the Eastern German engineer and university teacher Ulrich W. Hutter who gave wind power its present appearance. From 1939, he was head of the aerodynamics department at the Weimar School of Engineering and at the same time employed by Ventimotor, an SS-affiliated company that was fi.ir the even-

The aim was to produce decentralized wind turbines for Eastern Europe in the event of a final victory. But nothing came of it. Ventimotor's activities were discontinued in 1943.

Nevertheless, things went well for Hutter. In 1944, he received a teaching assignment in fluid mechanics and flight mechanics at the Technical University of Stuttgart. Hutter was himself a glider pilot and was also closely involved with the use of composite materials in aircraft development. This is how the world's first glider built entirely of glass fiber reinforced plastic (GRP), the
fs 24 Phenix" of the Akaflieg Stuttgart, with Ulrich Hutter. The glider ushered in a new era in aircraft construction in 1957. With the new miracle material, the wing profiles could finally be built as thin yet stable as the aerodynamicists' designs demanded - this was impossible with wood. The result was unprecedented flight performance. Today, the material is used in the latest generations of commercial aircraft such as Boeing's 787 Dreamliner and Airbus' A350 - and, of course, in every wind turbine.

Ulrich Hutter was also more active than almost anyone else in the field of wind energy. Hutter was the world's first to apply the principles of aircraft aerodynamics to wind turbine blades. It was also Hutter who placed the University of Stuttgart prominently on the map of international wind power research. His greatest achievement was to establish the construction of synthetic materials. The legendary StGW-34 wind turbine at Allgaier Werke in Uhingen near Stuttgart was his brainchild. Hutter was head of design there from 1946 to 1959. The StGW-34 is considered a milestone in the history of wind energy utilization and the prototype of modern "free-running turbines. It was the world's first wind turbine to have fli.igels made of composite materials and thus achieved aerodynamic dream values. The 17-meter-long, self-supporting rotor blades were the first of their kind in the world at that time.

At the time, this was an absolute innovation - and a risk: the material was largely unknown. Details such as the so-called loop connection", which is the transition from plastic to the steel threaded bolt (with which the blade is flanged to the hub), are still groundbreaking today. The two-winged 100-kilowatt turbine has been installed around 200 times worldwide. Even today, a discarded flugel adorns the university in Stuttgart-Vaihingen - and reminds us of the legend Ulrich W. Hutter.

Cradle of wind power
- how it all began
technology is evolution

We arrive in the 1970s. Generally, the wind turbines already look very similar to today's, only a number smaller. At the beginning of the 1970s, initiated by the 01-
price shock, politicians and industry began to think about an energy supply beyond oil, coal and uranium. At that time, no one could imagine what "renewable energies" meant. At most, the term "non-fossil and non-nuclear energies" was used. The German Aerospace Center had already begun to apply its expertise to the field of energy research in 1969. The institute is not far from the university campus in Stuttgart-Vaihingen. This created parallels, especially in wind power research. In 1976, energy research was established as a permanent research area at DLR.

Meanwhile, in the U.S., the space agency NASA was researching multi-megawatt wind turbines - and consulted the wind expert" Ulrich Hutter. The so-called MOD wind turbines with a rated output of up to 2.5 megawatts were developed. And in 1983, a giant also made its appearance in Germany: GroWian, the "Grol5e Windkraftanlage," stood on a 100-meter-high tower, had a rotor diameter of 100 meters and an incredible rated output of three MW. The idea for this giant came from Ulrich Hutter. As early as 1974, he was invited to the Federal Ministry of Research and Technology (BMFT) in Bonn. They wanted to know what wind could do for Germany. Hutter's prog nose: wind power could cover up to 73 percent of the country's electricity needs - the estimate certainly sounds less crazy today than it did back then.

GroWian was then built without Hutter, as is well known. A fatal mistake, as many think. Lightweight construction was virtually not an issue. The wings were supplied by the heavy machinery manufacturer MAN. Massive problems arose. At the point where the force was introduced into the hub there were defects. In short, the giant was not very successful. For the most part, GroWian stood motionless in the northern German landscape. In 1988, the plant was dismantled - a research fiasco costing 90 million deutschmarks. It is said that the energy companies involved wanted to use the machine to prove that wind power had no future. The opposite was to be the case, as we know all too well today.

Cradle of wind power
- how it all began
technology is evolution

At the same time, thousands of small wind turbines were being built in California. Oil price crises and growing environmental awareness drove the expansion. The tax legislation in California created a real wind rush for investors and turbine manufacturers. In total, around 16,000 wind turbines were built in the 1980s - the main beneficiaries were the Danish manufacturers of wind turbines, around half of which were imported from Denmark. At that time, there was little going on in Germany in terms of wind power technology. Ulrich Hutter, on the other hand, was honored: In 1986, the "Wind Energy Test Field Ulrich Hutter" in Schnittlingen, Baden-Wurttemberg, was named after him.

Then as now, political will played and continues to play an essential role in the wind power industry. Without the Electricity Feed Act of December 7, 1990, probably the world's first law on the feed-in of eco-electricity and the forerunner of the Renewable Energy Sources Act (EEG) of 2000, which is known worldwide and has been copied many times over, global wind power would certainly not be where it is today: an energy source with outstanding advantages.

There are now hundreds of thousands of wind turbines worldwide. A global industry has emerged. A single large turbine in a windy location can supply thousands of people with eco-electricity. The emissions generated during the production and construction of the turbines are offset within a few months by the production of emission-free electricity. After that, the wind turbines produce virtually no pollutants whatsoever. Could it be any greener?

There's no question about it: today's plants are technical marvels - packed with high-tech. Ulrich Hutter came up with many a detail. Many of them came from the pens of students from Stuttgart who either studied with Hutter himself or studied in his slipstream. It's clear:

Stuttgart plays a central role in the emergence of modern wind power.

And so it is hardly surprising that Germany's first university chair for wind energy was founded in Stuttgart (SWE). That was in 2004. And with Martin Ki.ihn, a proven expert in wind energy, a willing successor followed in Ulrich Hi.itter's footsteps to establish and lead the chair:
It was really exciting to develop and help build something new," recalls Ki.ihn.

Over the years, the turbines have grown enormously and advanced to become true high-tech machines: from a few kilowatts of power and a rotor diameter of 15 meters around 1980 to the current level of almost ten megawatts and rotor sizes of up to 180 meters. In comparison, GroWian is a pipsqueak! The University of Stuttgart has undoubtedly played its part in this success.

Many inventions and unrelenting ti.ifteering have made it possible for wind energy to be a global success today. It is difficult to pick out a single innovation that brought about the breakthrough. What has fundamentally changed the wind turbine is certainly semiconductor technology, says Po Wen Cheng, who has held the chair at SWE since 2011. Only with the inverter was it possible to implement the variable speed concept cost-effectively. This, in turn, made it possible to achieve the aerodynamic optimum even with fluctuating wind speeds and to reduce the fluctuations of electricity fed into the electrical grid. This technology has significantly improved the economic viability of wind energy - and taken the wind out of the opponents' sails.

Despite its success, wind power is still a tiny little light. Only about four percent of global electricity consumption is covered by wind power. But the prospects are all the brighter: The Global Wind Energy Council in Brussels says that wind could supply up to 30 percent by 2050. There is still plenty of room for maneuver, especially offshore: The potential offered by the existing ocean surface is many times greater than the global energy demand. Of course, Stuttgart is also at the forefront when it comes to offshore wind.

Renaissance of wind power
The 1990s
Birth of the Stuttgart Chair for Wind Energy

After Ulrich Hutter's retirement from teaching at the University of Stuttgart in 1980, it was quiet for a long time about wind power in the south of the republic. It was not until the 1990s that the wind picked up again. This was the time when the Greens were forming in Germany, the opponents of nuclear power were making waves, and interest in ecologically generated energy was on the rise. In short, the Germans are becoming more environmentally aware. The visionary idea for the Stuttgart Chair of Wind Energy - the first in the Federal Republic - was born in the wind of this spirit.

The year 1986 marks both a tragedy and a turning point: It is the year in which the nuclear industry's future trii:ums are blown up in Chernobyl. At that time, wind power generation played practically no role - in Germany, only 50 commercial wind turbines were in operation. In neighboring Denmark, on the other hand, there are already more than 1000 rotary aircraft. The Diinese are even exporting their wind riders to California, where huge wind farms are being built to give this supposedly new form of energy generation a foothold.

In Germany, the energy technology revolution is initially being glossed over. While nuclear energy was courted with billions of euros in research funding in the 1980s, wind power was of little consequence. And that's not all: Politics is putting obstacles in the way of the few willing windmullers: permits are extremely difficult to obtain.

But then two politicians, of all people, get things moving and turn the big wheel: Matthias Engelsberger (CSU) and Wolfgang Daniels (Grune), members of the Bundestag, recognize the situation of modern windmills. They draft a bill that is passed in the Bundestag on December 7, 1990: The "Electricity Feed Act". It guarantees the windmullers that the energy suppliers will give them

The company has to buy the wind power for a guaranteed 16.61 pence per kilowatt hour. A success that is tantamount to a revolution. However, in 1991, there was not yet all that much wind power that wanted to be fed into the grid: there were just 1,000 wind turbines in Germany at the time. But the energy giants already seem to have an inkling of what's coming - they are up in arms against the feed-in law.

Renaissance of wind power
The 1990s
Birth of the Stuttgart
Chair for Wind Energy

The Electricity Feed Act, which later became the Renewable Energy Sources Act (EEG), was undoubtedly the starting shot for a new age of wind power. The bang echoed through the entire country. Everywhere, resourceful tufters, engineers and scientists at research institutes hoarded its echo and began to develop wind turbines.

All the tuffers were also tapping into knowledge that had emerged years earlier in Stuttgart. There was a research department for renewable energies at the German Aerospace Center (DLR), which was intensively involved in solar and wind power. Some even say that all wind power and photovoltaic efforts in the Federal Republic started here. One of the employees at the time was Jens Peter Molly, a former student of Ulrich W. Hutter. At that time, Molly worked on the giant wind turbine GroWian and other research wind turbines. Later, Molly emigrated to northern Germany, where he helped establish and directed the German Wind Energy Institute (DEWI) in Cuxhaven. Jens Peter Molly's departures were Erich Hau and Henry Seifert. Both names are well known in the wind power world. They also started in Stuttgart.

While DEWI is gaining renown in the far north, wind power is largely in the doldrums at the University of Stuttgart. The wind pope Ulrich Hutter is long gone, only his partner Heiner Dorner keeps the wind flag flying high. But the enthusiasm for the power of the wind has always remained in the various institutes at the university. Following the Ara Hutter, special areas were worked on at the ISD (Institute of Statics and Dynamics of Aerospace Structures), the ICA (Institute of Computer Applications), which continued the wind-related work of the ISD, and the IAG (Institute of Aerodynamics and Gas Dynamics)," recalls Kurt Braun, who was at the university for a long time and has remained a loyal wind power fan over the years.

Another impetus to push wind power came from Brazil in 1992: The Earth Summit in Rio made climate change a global issue. Fossil fuels are pilloried, and the focus shifts to renewables. By the end of the decade, the number of wind turbines in Germany had increased tenfold to around 6,000 megawatts. The first wind farms and new financing models emerge. The German EEG quickly becomes an international hit and a blueprint for numerous other governments. To date, 61 countries have copied it!

Renaissance of wind power
The 1990s
Birth of the Stuttgart
Chair for Wind Energy

But the turbines that do exist are perceived by many as sti:iring. There is talk of making the landscape greener. In addition, the early wind converters are deafeningly loud. In short, acceptance among the population is rather low at the time. One thing is clear: If wind power is to make it big, it has to be better. The Stuttgart-based company recognizes this and dedicates itself to the subject of acoustics. To this end, they develop a research turbine called UNIWEX, which is installed on the test field in Schnittlingen. Its results are groundbreaking, recalls Kurt Braun:
Pioneering work was done there. It was possible to halve the noise level. It was primarily the work of the researchers at the **IAG that** brought about the breakthrough.

As wind power picks up speed, the story of Germany's nuclear phase-out begins. The year is 1998, and after winning the election, the red-green coalition under Gerhard Schroder sets about implementing the phase-out of nuclear energy promised in the election campaign. In 2000, the decision is made to gradually decommission Germany's nuclear power plants: the last reactor is shut down in 2022.

At the time, a man known as the German Daniel Dusentrieb or **Bill** Gates was right at the forefront: Aloys Wobben. In the East Frisian town of Aurich, he tinkered with the future of German wind power. He built his first turbine in a shed as early as 1984. His company, Enercon, quickly grew into a medium-sized business. In 1992, the East Frisian made a breakthrough: the gearless wind turbine. The new machines run better and more reliably and are soon regarded as the Mercedes of the industry. Wobben's company quickly became one of the big players on the market.

The 1990s and 2000s saw the introduction of numerous technological innovations in wind power. In particular, the transition from stall to pitch turbines was a milestone. At the stall systems, only the blade tips rotate out of the wind to slow down the turbines in an emergency; with pitch control, the entire blades rotate, allowing much more precise load and power settings. Ulrich Hutter's pioneering spirit was to be seen here as well: Fruhe plants of his already had pitching blades.

Wind turbines were also becoming larger and more powerful. This was made possible by variable-speed turbines with inverter technology. A supplier industry with well-known names and numerous employees grew up around wind power: ZF, FAG, Flender, Liebherr... For a long time now, it has not been the tufters who have been driving wind energy forward, but the large industrial groups that have conquered a new branch of the economy.

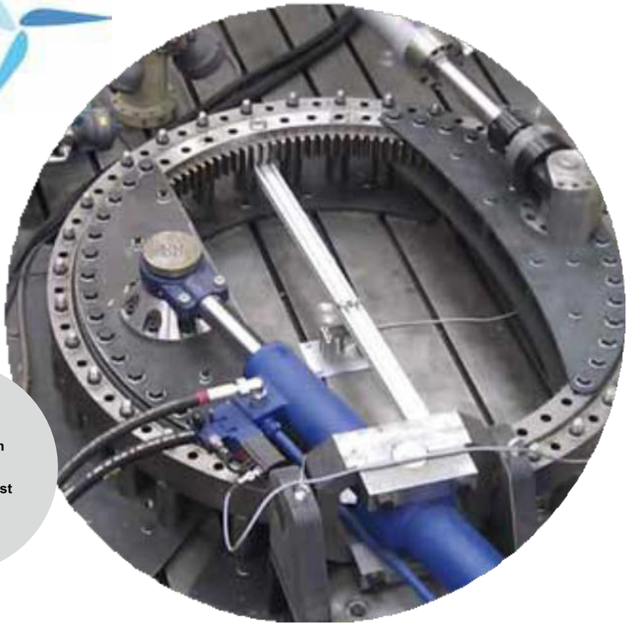
Renaissance of wind power
The 1990s
Birth of the Stuttgart
Chair for Wind Energy

In Stuttgart, too, wind power research is gradually awakening from its slumber: Heiner Dorner, at the time the last wind power Mohican at the University of Stuttgart, takes a telephone call in the fall of 2002 that was to have far-reaching consequences for the wind power world. On the other end is Karl Schlecht, founder and chairman of the supervisory board of the concrete pumping company Putzmeister, a multi-million dollar company based near Stuttgart. Karl Schlecht is a fan of wind power and has just read Darner's book about Ulrich Hutter and wants to get rid of some money: "I plan to donate five million to a professorship," Schlecht lets Dorner know on the phone. Shortly thereafter, the two meet and agree to found SWE.

When I announced the generosity of the foundation, I felt like the 'midwife' of the new-old teaching and research field of wind energy in the faculty: finally more staff, more research funds, better student support and training. There would soon be an independent wind energy institute with an endowed professorship, simply a dream after the many years of fighting alone," Heiner Dorner said happily when he presented the plans to the university management.

In 2004, the time had come: SWE, the first German chair for wind energy, was founded in Stuttgart.

Foundation years
Achievements of SWE between 2004 and 2014



Leaf pitch system
and
Blade Bearing Test Stand

After the wind boom triggered by Ulrich Hutter and the research efforts at DLR, it became quiet about wind power at the University of Stuttgart. However, the wind never completely died down: from 2004 onwards, it blew again with full force. In the years that followed, the University of Stuttgart put itself on the global map for wind energy research and produced numerous innovations and even world records in the traditional manner. It was not an easy task to establish this wind energy chair, to recruit dedicated staff for research and teaching, to initiate research projects, to develop the curriculum for teaching and to give the chair a sharp research profile. It has been more of a constant challenge as more and more universities and research institutions have discovered the importance and attractiveness of wind energy research. But one thing is clear: All the efforts were not in vain. Some highlights are presented here.

LiDAR
Tracking the wind

Scientists at SWE have been researching laser-truncated measurement methods since 2008. 1 Their goal is to analyze the wind flowing toward the turbine and to prepare the turbines specifically for this. This increases energy transfer and reduces loads. The Swabians are world leaders in this technology.

Modern wind turbines impress by their sheer size. It is not unusual for their towers to be well over 100 meters high and their blades up to 90 meters long - true giants. But such dimensions make it difficult for research: Measuring and characterizing wind fields with conventional measurement methods is becoming increasingly complicated and expensive. Until now, monstrous lattice towers have been erected that reach the same height as the wind turbines themselves. The measuring masts are equipped with all kinds of measuring devices. Often enough, not a single mast was enough, but several - in front of and behind the turbine - were needed to get a complete picture. Since the triplanes climb to record heights, measuring with masts is simply too expensive.

So what to do? The answer from David Schlipf of the Stuttgart Chair of Wind Energy: measure without contact. Similar to commercial aircraft, which have a weather radar installed in the front of their nose and constantly monitor the weather, wind fields near the ground can also be scanned with a laser. This has been done for several years - and SWE scientists have played a major role in this innovation.

The technology used is called LiDAR - Light Detection and Ranging. The devices are about the size of a suitcase, can be carried by two people and can be conveniently placed in different locations. In principle, this technology works like radar: LiDAR systems for measuring wind fields emit laser pulses. When these hit particles in the air, such as water, the tri:ipfchen or dust particles, the beams are reflected. This happens thousands of times per second, in a precisely defined area. In this way, ultra-high-resolution short-term predictions are obtained.

The knowledge gained is invaluable. To understand the significance, one must know that the area covered by the rotor of a modern multi-megawatt wind turbine is over 20,000 square meters. That is roughly equivalent to two soccer fields. Of course, in such a huge area, the wind is not i.ubiquitous and blows from the same direction. Let's assume the tower is 130 meters high and each fli.igel is 80 meters long. When the rotor blade passes the highest point, it reaches a height of 210 meters above ground. The opposite blade, which passes through the bottom point at about the same time, is only 50 meters from the ground. Every child because5 of kite flying: the wind blows stronger further up. For such a giant as a wind turbine, this means enormously fluctuating loads acting on the bearing and the drive shaft. Added to this are shear winds that suddenly hit the fli.igels from a completely different direction. Because5 you know about this before the wind hits the rotor - and thus loads the entire structure - you have a clear advantage. You can turn the blades on in time, i.e. pitch them out of the wind, and thus reduce the loads acting on them. At the same time, the lifetime of the plants is increased and the energy production costs are reduced.

The Stuttgart researchers have even gone one step further: They installed the LiDAR system directly on the nacelle of the wind turbines and use the data obtained to control the turbine. In 2012, they were the first researchers in the world to prove the feasibility of this system. Together with researchers from the renowned National Renewable Energy Laboratory (NREU) in Boulder, USA, Schlipf and his colleagues from SWE had controlled a wind turbine using a LiDAR system mounted on the nacelle. Instead of looking up from the ground, the laser looks horizontally in the direction from which the wind is approaching the turbine. To make this possible, the researchers led by David Schlipf developed an optical system that deflects the laser and brings it from the vertical to the horizontal. But that alone was not enough: ,,LiDAR has been far too slow up to now," says Schlipf. So the scientists gave it a leg up. Now the laser can scan much larger areas in a much shorter time. The effort has paid off: Since then, the researchers have received a much more precise measurement signal - and a much more detailed image of the wind field.

But LiDAR alone is not enough. The flood of data delivered by the laser beams must also be evaluated and interpreted. And converted into concrete commands for the turbine control system, so that, for example, the rotor blades turn out of the wind or the nacelle adapts to the changing wind directions. This is done by software called "Witlis" - which was also developed by the Stuttgart-based company.

The significance of the work of the SWE researchers led by David Schlipf for the wind energy world becomes clear when one thinks of large wind farms. Hundreds of wind turbines can be found here, side by side and one behind the other - and sometimes take the wind out of each other's sails. The turbines influence each other. Behind the wind turbines is basically a hole in the wind - but with increased turbulence," says Schlipf. In some cases, the turbines also interfere with each other due to turbulence. If you know in advance how wind fields move through large wind farms, you can plan the layout, i.e. the arrangement of the wind turbines, accordingly. Such measures can greatly increase the overall yield of large wind farms while reducing damage. Selected wind turbines in large farms will certainly be equipped with such LiDAR systems in the future - and warn the other wind turbines when it becomes dangerous. This in turn allows

Long Range Lidar in the Baltic 1-0ffshore Wind farm

The new technology makes it possible to design the wind turbines with greater filigree: Since the loads are reduced, the towers and rotor blades have to withstand lower forces and can therefore be built with less safety impact.

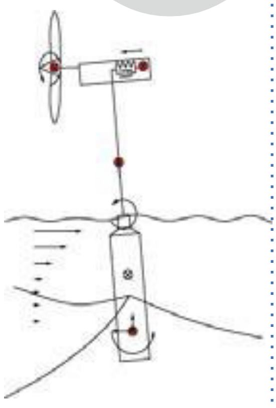
All in all, David Schlipf and his colleagues have invested thousands of hours of work in the LiDAR: "I spent three years working on the subject full time," says Schlipf. Such dedication to wind power is naturally rewarded: David Schlipf's doctoral thesis was honored with the "Excellent Young Wind Doctors Award 2016". The prize is awarded annually by the European Academy of Wind Energy (EAWE) for the best European doctoral thesis in the field of wind energy. In the wind industry, David Schlipf has since been regarded as the spiritual father of LiDAR-controlled wind turbines. And that's not all: at the same time, he received the Otto F. Scharr Prize for Energy Technology.

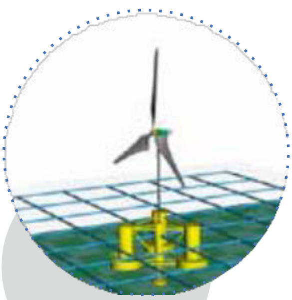
And then there is Schlipf's spin-off company called Sowento. With this company, Schlipf and his team offer services related to the control of wind turbines - including, of course, LiDAR-based control systems. The spin-off soil will help pave the way for the commercialization of LiDAR-based turbine control. This is a perfect example fi.ir what the Karl Schlecht Foundation stands for: Stimulating innovation through research and exploiting scientific findings through entrepreneurship.

Floating Wind
Wind power floats free

Foundation years
Achievements of SWE
between 2004 and 2014

Reduced simulation model of a floating Wind turbine





Floating simulation

They float in the sea like oversized floats on a fishing rod. Or they are pulled under water by thick steel cables and thus held in a stable position: We are talking about floating foundations for wind turbines. In recent years, more and more turbines of this type have been appearing. These offshore wind turbines are not supported by fixed foundations on the seabed, as is the case in the North and Baltic Seas, but are kept afloat with the help of buoyancy bodies and mooring systems.

Die Technik hat einen herausstechenden Vorteil: Sie erlaubt es, auch tiefe Gewasser fur die Windenergie zu erschliefsen. Und das sind global gesehen die allermeisten: Egal ob rund um den Atlantik, das Mittelmeer oder vor Asien - fast uberall fallen die Kusten steil ab, wird das Wasser rasch Hunderte Meter tief. Aufgrund der immensen Baukosten jedenfalls zu tief fur Windrader, die sich auf grofsen Stahlgestellen oder monstrosen Rohren am Boden abstutzen. Zu schade: besonders uber tiefen Gewassern wehen starke Winde. Diese Ressource will man unbedingt anzapfen. Wissenschaftler sagen: Das Potenzial durch die vorhandene Meeresoberflache sei um ein Vielfaches grofser als der globale Energiebedarf.

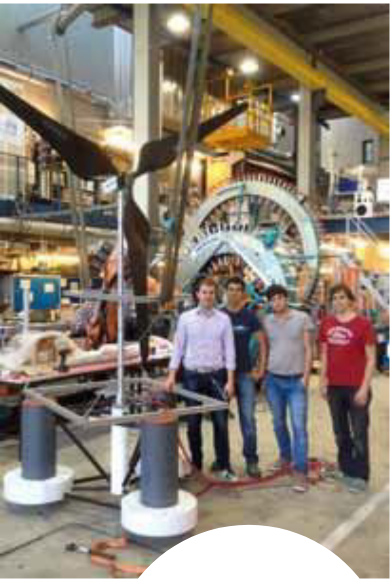
These are not bold visions. Test facilities have been in the water for a long time. Off the coasts of Norway, Scotland, Portugal and Japan, for example. Some machines are pulled underwater by enormous ropes and chains and stabilize themselves in this way, while others try to compensate for the rocking motion of the waves and currents at sea with sophisticated ballast water systems. It is not yet possible to say which of these float concepts is the most promising, as the floating wind industry is still too young for that.

SWE

Foundation years
Achievements of SWE
between 2004 and 2014

But one thing can be said with certainty: Scientists and students at the Stuttgart Chair of Wind Energy have been working diligently on the development of floating wind power for years. They have been involved in numerous projects and have gained new insights. Efforts to develop the new floating wind power technology began in 2009, when Denis Matha, who is no longer with SWE, laid the foundation for the Stuttgart team's research into floating platforms for wind turbines. He established contact with the National Renewable Energy Laboratory in the USA, which was also conducting initial research on float concepts.

The Stuttgart-based company has contributed its expertise in the field of swimming wind to numerous projects. In the EU project AFOSP, a partner project with the Technical University of Barcelona, the aim was to design a so-called Spar float. Spars are long cylindrical floating skis that float upright in the water. Usually, these cylinders are made of steel. But steel is expensive and complicated to process. The research project therefore aimed to test a variant made of be clay. While the Spaniards built the prototype on a scale of 1:100 and tested it in the water tank, the Stuttgart team was responsible for the concept design and dynamic load simulation. The project has now been completed. The industry's interest in the results was enormous," says Friedemann Borisade. In the meantime, his colleague Dennis Matha has become involved with the International Electrotechnical Commission (IEC) in Ghent and, together with other experts, has drawn up standards for the design of floating wind turbines.



Modell of a floating offshore wind turbine for shaft refueling tests

Another project in which the Swabians were involved is ,,INNWIND.EU". This involved the design of floating wind turbines with a rated output of ten megawatts and more. The Stuttgart wind researchers once again demonstrated their expertise: they built a platform model, weighing 150 kilograms, two meters high and tested it extensively in the wave channel in Nantes, France. The central questions here were: How do you test such a downscaled concept? How can previous tests of downscaled concepts be improved?

Floating offshore
Wind turbine

What new measurement technology is promising? To date, there has been little expertise on the interaction of aero- and hydrodynamics. Here, too, the SWE researchers have gained important insights.

While the industry is setting up the first small floating test wind farms with several identical turbines, for example off the coast of Scotland, the research in the EU project
LIFES50+" is already about how future giant wind farms can be realized floating in deep water. The key questions here are: How can construction and operating costs be reduced? Which simulation method is advantageous at which step in the design process? SWE researchers are also contributing their know-how to this question.

The "FLOAT GEN" project, which has been running since 2013, is also of international significance. A 5,000-ton floating platform is currently being built in France by the company ma Ideol to support a two-megawatt wind turbine. The turbine went into the water in 2017. Thanks to their extensive experience in evaluating measurements at the Alpha Ventus research wind farm, the Stuttgart-based company is contributing to this demanding measurement campaign. They are supporting the design of the turbine with numerous sensors and want to find out whether the assumptions made for the design of the turbine were correct. Such measurement data from prototypes are important for validating our simulation tools," says Friedemann Borisade. This knowledge then helps to save material, time and costs when building further plants. So far, the company has relied on data and experience from the construction of offshore oil and gas platforms. But that doesn't always fit, because the rotor has a big influence on the floating plant," says Borisade.

Foundation years
Achievements of SWE
between 2004 and 2014

As you can see, the wind researchers in Stuttgart have set their sights on the open sea - and have thus set the right course for our energy supply: Experts firmly believe that floating wind power will play a key role in energy supply in the future.

The Stuttgart researchers are currently involved in other projects: MALIBU involves a floating buoy equipped with a so-called LiDAR measuring device. These instruments measure wind conditions with their laser beam and thus provide information on whether the construction of a wind farm is worthwhile. However, questions still need to be answered about whether the movements of the buoy in the water will affect the wind measurements. In another project, which also involves floating turbines with ten or more megawatts and which are to be erected quickly and easily by means of a telescopically extendable tower, the Stuttgart researchers are working on special control software that will make it possible to control the turbine automatically during operation. Due to the gri:itser movement on the water, controlling floating wind turbines is more complicated than with fixed foundations.

And then there is the float concept developed by the Stuttgart team of Frank Lemmer, Wei Yu, Kolja Muller and Friedemann Bo risade in collaboration with specialists from the Technical University of Denmark and the Spanish Centro Nacional de Energias Renovables: The ,,TripleSpar" - a hybrid of a submersible platform and an economizer buoy, for a ten-megawatt wind turbine. The Stuttgart-based company has equipped a model of this turbine with an innovative control system and tested it extensively in Kanai. The initial results are promising.

Ultimately, the success of floating wind turbines depends on how quickly, reliably and economically floating wind farms are implemented. It remains an exciting topic for the Stuttgart-based company, as there will certainly be no shortage of new challenges in the coming years.

WindForS
Research with combined forces

Even though the wind blows mainly in the north of the country, wind power is being researched eagerly in the south. There is a simple reason for this: large parts of the world are not flat, but mountainous - just like southern Germany, the cradle of modern wind power, some say. Such special requirements need special research. That's why the WindForS research network exists.

There is no question that wind turbines are also worthwhile in the south of the country, in the hugeligen Bin nenland. If we want to achieve the energy turnaround, we cannot avoid expanding wind power in inland areas. But hilly terrain places very different demands on wind turbines. The topography, i.e. the nature of the terrain, has an enormous influence on the air currents that the turbines have to cope with. On flat terrain, the flow is much easier, but it is not the rule on our planet.

Wind energy in complex terrain:
a central research **topic for WindForS**

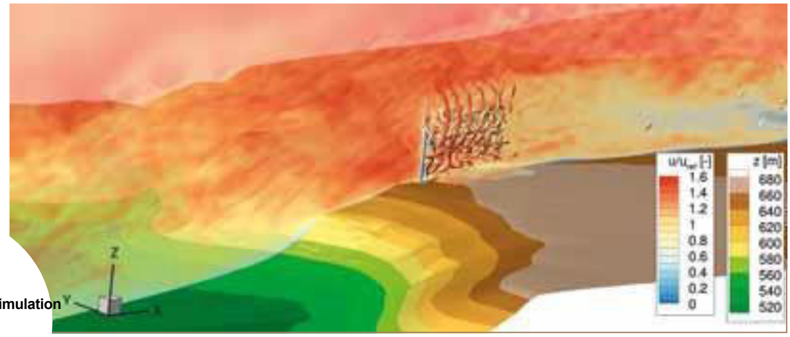
The global wind research community has recognized this and WindForS-the wind energy research cluster (the large S marks the southern German region) aims to make a major contribution to this and establish itself as an excellent partner for questions related to wind energy in the complex terrain. The wind power specialists in the network are striving to advance wind power research especially for the mountainous complex terrain. In this field, WindForS wants to establish itself globally as the contact partner," says Andreas Rettenmeier, who headed WindForS until recently.

Initiated in 2010, the network was founded on June 6, 2011, with the aim of making southern German wind power research visible to the world. The network combines the expertise of 26 institutes and chairs from Bavaria and Baden-Wurttemberg. They work in the fields of meteorology, landscape architecture, soil mechanics and foundation engineering, rotor aerodynamics and airflow reduction, design and calculation of structures and supporting structures, materials, construction methods and manufacturing technology, testing and measurement technology, operational reliability and maintenance as well as operational management, storage technologies, grid connection and integration.

In addition to SWE and other institutes of the University of Stuttgart, the members include the University of Tubingen, the Technical University of Munich, the Karlsruhe Institute of Technology, the universities of Aalen and Esslingen, and the Center for Solar Energy and Hydrogen Research Baden Wurttemberg (ZSW). The members cooperate not only in research, but also in education and training.

The WindForS network was also the initiator of the new research wind test field on the Schwiibische Alb near Geislingen. It is the successor to the venerable Hutter test field. To this end, the KonTest project was launched. This project focused on what the test field would look like, what it would be able to do, and what it would be used for. In the meantime, the project has been completed, and construction of the test field is moving forward. The follow-up project, WINSENT - Wind Science and Engineering in Complex Terrain, is now specifically concerned with realizing the wind energy research test field at a specific location in a mountainous and complex terrain.
The research projects VORKAST and TremAc are also worth mentioning. In VORKAST, the scientists of SWE and ZSW are concerned with short-range forecasts of the wind power of

individual wind turbines and wind farms by means of corn-.



WindForS Str6m simulation

The project focuses on the combination of LiDAR measurements with a high temporal resolution and a long range (up to ten kilometers) with additional meteorological data. The same applies to the short-term forecasting of photovoltaic systems with a new type of cloud camera and the integration of neural networks. The goal of VORKAST is to be able to predict both wind and solar power as accurately as possible, for example to optimize the operation and management of storage facilities (power-to-gas, battery, flywheel, etc.)," says Rettenmeier.

In the TremAc project, the effects of acoustic and corpus sound from wind turbines on the environment are being researched. Here, for example, the scientists are looking at structure-borne sound. How does a wind turbine affect the ground during operation? Do the wind turbines transmit sound to neighboring and inhabited areas and what are their influences? What penetrates how far into the ground and releases what? What are the effects of acoustic emissions from wind turbines and how can they be reduced? Scientists from the Karlsruhe Institute of Technology, the University of Stuttgart and the Technical University of Munich are addressing such questions from a technical perspective. Psychological and medical investigations are being carried out by specialists from the University of Bielefeld and the Martin Luther University of Halle-Wittenberg as part of the research project. This interdisciplinary cooperation is urgently needed, because the perception of sound and vibrations has strong psychosomatic components that must be considered together with the objective measurements.

The network also includes specialists who are supposedly outside the field. Landscape architects, for example. They research how wind

This is important for countries with a high population density, because the landscape could be changed by the increasingly large wind turbines. Landscape integration creates a platform for dialogue. This, in turn, increases the acceptance of wind power, especially by the direct residents of the wind power plants, and contributes to its success.

One project that is specifically dedicated to offshore wind power is: ,,WIPAFF - Windpark-Fernfeld". The aim of the project is to contribute to the impact of the large offshore wind farms planned and partly already under construction in the North Sea on the regional wind field and the regional climate. In this way, the project participants want to make their contribution to planning security for the expansion of wind farms. They are developing numerical and analytical simulation models for the far field (ten to 100 km) of large offshore wind farms. They also investigate the wake effects in the far field by means of in-situ, aircraft and satellite observations. They create bases fi.ir options for action fi.ir the further expansion of offshore wind energy. The focus of the investigations is both on effects that have a direct influence on the yields of wind farms in the North Sea and on changes in the regional climate in the coastal regions adjacent to the North Sea.

Ultimately, the aim of all WindForS researchers is to increase acceptance of wind turbines, make them more efficient and open up new areas for wind power by creating a sound knowledge base as a basis for argumentation.

In order to keep all these research projects going and all partners involved up to date, all WindForS participants meet several times a year. In addition, topic-specific meetings and workshops are held as needed. These meetings always generate ideas for new research projects. In this way, the wheels keep turning. The future of wind energy research has many facets and the challenges can only be mastered through close cooperation between WindForS partners. So the excitement continues.

InVentus wind in the tank

In the InVentus student project, young men and women from various disciplines are contributing their expertise: they are designing and building a vehicle that is powered solely by the wind. They are record-breakingly good at it.

You can see immediately that this car is different. Instead of a crackling combustion engine, it has two carbon-fiber rotors that turn their laps in the wind. A moving wind turbine? That's exactly what the Ventomobil is. The sleek black roof, reminiscent of a glider cockpit, doesn't just roll along with the wind in its wake, but drives precisely against the wind. This is the maxim of the Aeolus Race, which has been held every year since 2008 in Den Helder, the Netherlands, and in which numerous teams from all over the world participate with their self-built vehicles. The goal: to drive faster than the wind blows. And in the direction from which the wind blows.

Team Inventus

How does that work? It's very simple," explains project manager Julian Fial from the Institute of Aircraft Design at the University of Stuttgart:
The sum of all resistances - from the gearbox to the wheels to the rotor blades and the vehicle's dynamics - must be less than the energy we can extract from the wind. The key is that the faster the vehicle travels against the wind, the higher the so-called relative wind speed, i.e. the strength with which the wind blows into the rotor. Heil5t: The stronger the wind blows, the faster the Ventomobile travels.

First things first: InVentus is a learning platform for students at the University of Stuttgart. The project brings together students from different disciplines, such as lightweight construction, wind energy, mechanical engineering and electrical engineering - just like a real wind turbine. The bachelor's and master's theses are designed in such a way that they always include an organizational partil to move the pro ject forward. The project is primarily supported by SWE and the Institute of Aircraft Engineering (IFB). Specialists from the Institute of Aerodynamics and Gas Dynamics (IAG) and various industrial sponsors are also involved. The Karl Schlecht Foundation helps out with money to finance purchases and travel to the races.

The goal of InVentus is to get students excited about wind energy and give them the opportunity to gain experience in a complex project - and above all to have fun. The project is a great advertisement for the university, as it demonstrates the competence of Stuttgart students in numerous publications and television reports around the world.

The idea for InVentus came from the students themselves.
Actually, the students wanted to build a snowboard that would be pulled by the wind with a kite," recalls Martin Kuhn, who held the chair at SWE at the time. But that was a bit too crazy for us. Then came the competition with the wind-powered cars and everyone was heil5 on it. Surprisingly, we took first place straight away."

That was in 2007, when the two students Jan Lehmann and Alexander Miller started building the first Ventomobile. It was their final project. The vehicle

Inventus - a vehicle driven by the wind

Foundation years
Achievements of SWE
between 2004 and 2014

consisted of a carbon fiber chassis and a rotor whose kinetic energy was used directly to drive the wheels. There were no electronics of any kind in the vehicle. In any case, the three-wheeled automobile had to be as light as possible. Professor Martin Ki.ihn recalls that he succeeded: I'm a design engineer myself and often took a much more conservative approach to the design. The students really had a lot of confidence and showed that it was possible. Their efforts paid off: Lehmann and Miller won the Boysen Prize in 2009.
- fi.ir the best diploma thesis in the field of environmental engineering.

Over the years, a total of three vehicles were developed
- and also built themselves in the university's diverse workshops. The latest generation is a true marvel of technology and combines numerous areas of the university - now also electrical engineering. This is because the racer, which weighs around 150 kilograms, is a hybrid: Two rotors capture the wind and together produce a nominal output of around 4.5 kilowatts at maximum power. In this way, the Stuttgart-based company went to the maximum of what is permitted by the racing regulations in terms of rotor surface area. One rotor delivers its torque directly to the wheels, the other drives a small generator, which in turn fi.itters an electric motor.

But the complex hybrid drive has only paid off to a limited extent. The system is enormously complex," says Julian Fial. The problem: The torques of the two input shafts (one mechanically driven by the wind and one electrically

An old version
of the Inventus vehicle

driven) are combined in a branched planetary gear. But: sometimes they influence each other. In some cases, they even interfere with each other. That's why the Stuttgart team competed in the 2016 Aeolus Race without an electric drive - but still came in second. Team InVentus even surpassed its own previous record and improved its best performance: 78 percent of the wind speed, which on this day was 15 kilometers per hour. On days with strong winds, we even managed 27 kilometers per hour," says Fial. Only the Danes were faster. They were sailing at 101.76 percent of the wind speed. In other words, they were actually faster than the wind. In the acceleration discipline, however, the Swabians left all the other teams behind.

In 2017 - so much ambition is necessary - the SWE racing team wanted to win again. But things were to turn out differently. The Canadian team ChinookETS was faster and even screwed the world record from the previous year to a new level: 102.45 percent. The Danes from the DTU in Copenhagen were also faster - which put the Stuttgart team in third place.

The Swabians around Julian Fial take it calmly: The Canadians and Danes put in a great performance this year and deserved to win. But that only motivates us even more now to push our vehicle further and race for victory again next year."

G

Alpha Ventus RAVE
Accompanying research on Germany's first offshore wind farm

Foundation years
Achievements of SWE
between 2004 and 2014

When the first wind turbine blades rotate at the Alpha Ventus test site in August 2009, all anyone sees are the gigantic turbines. Hardly anyone has any idea how many tiny measuring instruments are installed in the blades, towers and steel foundations, and how much work is involved in evaluating the enormous volume of data. In the process, the data provide a sea of insights.

Alpha Ventus is not just any wind farm. It is the world's first offshore wind farm dedicated purely to research. Its construction was followed by the entire wind power world. Never before have so many, so large wind turbines been erected so far out at sea. There's no question that we're not talking about wet seas here, as was the case with the turbines that stood in shallow water back then, but about real offshore wind trippers: Alpha Ventus is located in the German Bight, about 40 kilometers off the coast of Borkum. The weather conditions here are extreme: the wind regularly whips with gale-force winds over the up to 17-meter-high wave crests.

Wind turbine at Alpha Ventus offshore wind farm

Setting up a wind farm at such a location was an enormous challenge - pretty much everything was new territory. A lot of money was spent on learning the ropes. But Alpha Ventus is not a normal commercial wind farm, but a gigantic test platform for offshore wind power, from the logistics of construction to operation and maintenance. The same is true for environmental compatibility. It is clear that the construction and operation of such a plant requires gri.ind research. It is also clear that researchers from the University of Stuttgart should not be absent from such an important project.

The research project ,,RAVE - Research at Alpha Ventus" soil show whether it is possible to generate electricity economically and reliably in the middle of the North Sea. The project started before the wind farm was built and continues to this day. It is the most extensive and ambitious offshore research project the world has ever seen: Over a hundred and fifty scientists are investigating how wind, weather and waves affect nacelles, steel towers and rotor blades, whether they can withstand the stresses far out at sea for twenty years, what impact the turbines have on the sensitive oceans of the North Sea and how laser systems can optimize wind measurements on the high seas and thus make the operation of the offshore farms more economical.

Specialists from SWE and the University of Stuttgart played a major role in the two subprojects OWEA - Verification of Offshore Wind Turbines - and OWEA-Load. The researchers primarily contributed their expertise in LiDAR. The main focus was on physical aspects: How does the wind flow into the park and how does it behave behind the turbines? In order to find this out, the Stuttgart researchers supervised various laser measurement systems. In some cases, the researchers had to travel around the park themselves, climb the gigantic turbines and install the sensitive measuring instruments. Sometimes they had to wait weeks for good weather with little wind and waves. Such weather windows are rare, schliel51ich is why the park was planned where the weather tends to be rough - to harvest a lot of wind, i.e. to produce a lot of electricity. When the weather is finally right, everything has to happen very quickly. But in order to be able to work in the park at all, the scientists must first complete special offshore training. In short, the effort is enormous.

But: The oats that the Stuttgarters analyze are worth it.

Lidar on the Gendel of a Offshore wind turbine

Acceleration and bending moment sensors on the rotor blades reliably record the loads. The same applies to environmental conditions such as wind, waves, temperature and sea current. This allows the correlation between environmental conditions and loads to be deciphered. Or the torques in the drive train, bending moments in the tower and the foundation.
- In total, i.iber 200 sensors measure continuously in each plant. There are gigantic mountains of data, many, many terabytes.

The Stuttgart researchers are currently evaluating the data. They are particularly interested in wake, the turbulent airflow that occurs when the wind field has passed through the rotor - one of the Stuttgart researchers' areas of expertise for decades. It can be compared with the wake vortices of airplanes. These currents obstruct wind turbines further back. They not only take the wind out of their fli.ights, but also burden the turbines with strong turbulence. The Stuttgart researchers are taking a close look at the loads acting on the turbines. Whether the wind turbines work long enough under such conditions. Or whether they still have enough reserve for the expected service life. This opens up new possibilities for wind farm operators in terms of extending service life and increasing performance.

The findings also help to optimize the control of the individual wind turbines. This is referred to as pradictive control. The focus here is on using LiDAR measurements to pre-control the collective blade angle. This was achieved with the LiDAR system developed at SWE, which was successfully tested for the first time in the world together with the U.S. American research institute NREL. In the same way, the researchers are analyzing the layout of the wind farm. Here, too, there is room for optimization in order to ultimately increase the overall yield.

Often it is better to drive those wind turbines in the first row somewhat throttled, for example by a slight skewing of the turbine. This allows the wake to be deflected so that it does not hit the rear turbine. This leaves more "good" wind with higher wind speeds and less turbulence for the rear rows. Ultimately, the total output of the wind farm can be increased. At the same time, the series of measurements have shown that it makes sense to create a customized maintenance plan for each wind turbine. After all, not all turbines are equally loaded. Turbines on the outer sides have to deal with different currents than propellers in the center of the park. The ac tive control of individual wind turbines, i.iber data obtained with LiDAR on the nacelle, is also promising. Here, the SWE researchers have done important pioneering work. Naturally, turbine manufacturers are also interested in the research results. After all, they can use them to assess whether their plants are correctly dimensioned.

In order to optimize all the processes in future wind farms with hundreds of turbines, the Stuttgart researchers led by their professor Po Wen Cheng are developing a simulation environment. It allows the system properties of the entire wind farm to be mapped for optimization. This will make tomorrow's wind farms, which will one day supply a large part of our electricity, even more efficient.

FINO research platform in front of the Alpha Ventus offshore test field

Teaching and Alumni
Former students remember their time at SWE

Wind energy excursion students on a turbine in the Black Forest

The Stuttgart Chair of Wind Energy (SWE) is anchored as a chair at the Institute of Aircraft Engineering of the Faculty of Aerospace Engineering and Geodesy at the University of Stuttgart. The task of the chair is not only excellent research, but also solid training to prepare students for the challenges of the future.

In the meantime, up to 18 staff members were working at the chair. The wind energy lectures, which were attended by only about 15 students in the early years, are now extremely popular. Sometimes they are filled to capacity. Then, up to 200 students listen to the lectures of the top-class lecturers. No wonder: The studies at SWE have an excellent reputation - and wind power students from Stuttgart are welcomed with open arms by the industry.

The philosophy of the Wind Energy Chair is a combination of solid theoretical knowledge coupled with practical application, where students have the opportunity to use simulation programs to model the behavior of the wind turbine and wind farm. Additionally, there is the option to put theory into practice through project work and labs.

Professor Po Wen Cheng, chair of the department since **2011,** knows the reason for SWE's success: "Wind power reduces our dependence on 01 and gas imports,
avoids CO2 emissions, creates new jobs, and does so without radioactive risk."

Teaching and Alumni
Former students remember their time atSWE

Here is a small excerpt from former students at SWE:

Sebastian Kaus began studying renewable energies in his bachelor's degree in 2009: "I learned about the InVentus project in my very first semester because my roommate was on the team. In the first semesters, I built rotor blades and thus gained my first practical experience with wind energy." Over the years, Sebastian Kaus took on further assemblies on the vehicle and was team leader for three years at the end. During this time, he developed two new vehicles and won many podium places as well as the Innovation Award for wind energy cars at the annual race in Den Helder. SWE has always supported us and made a lot of things possible. In particular, we often called on the measurement technology group led by Jan Anger and Martin Hofsals to carry out wind tunnel tests at the IAG or to use the generator test rig for our own experiments. Professor Cheng has always left us free space and thus enabled us to dare new things."

Thanks in part to his experience at InVentus, Sebastian Kaus found his way to Senvion GmbH in Hamburg after completing his studies. For the past two years, he has been analyzing wind turbine data in order to keep them operating at optimal performance and without errors. The theoretical and practical knowledge from my time at SWE, where I was also a student assistant and wrote my bachelor's thesis, helps me a lot to do my job efficiently and well," says Kaus.

Matthias Arnold came to SWE as a student in 2006, where he spent a total of around ten years. Matthias Arnold also became heavily involved in InVentus: The challenge of developing a wind-powered vehicle sounded very exciting, even though I had no idea about wind energy at the time. In the first year of InVentus, Arnold was responsible for developing the rotor hub and the on-board electrical system/sensor technology. So he inevitably had to get involved with wind energy. Arnold's fascination with wind energy led him to study wave and tidal power generation in his fifth semester as an industrial intern at the mechanical engineering company Voith. His example is a good illustration of how different renewable energy technologies can be combined and the diversity that the SWE program offers. In his student research project for the InVentus project at the Institute of Aerodynamics and Gas Dynamics, Arnold worked on an aerodynamic fairing for the Windmobile.

Participants of the Doctoral Seminar of the European Academy of Wind Energy (EAWE)

SWE

Teaching and Alumni
Former students remember their time atSWE

His diploma thesis was similar to the student research project: With this work, the previously parallel running Strange van tidal stri:imation energy and wind energy came together, since it was a matter of transferring stri:i mation simulations and phenomena directly back and forth between the technologies.

Then came the change of sides: After my studies at SWE, Professor Cheng hired me as a research assistant and doctoral student. There, I worked on the hydroelasticity of tidal stri:imung turbines. At the same time, I was involved in teaching at the institute. I particularly remember the appreciation of good work. It was also nice that, as a doctoral student, you were allowed to present your work at international conferences if the publication was appropriate. That's how I got as far as Alaska and Hawaii."

Matthias Arnold has now landed in Germany's high Nor den: at the wind turbine manufacturer Enercon in Aurich. There, he works on highly detailed aero-dynamic and aero-elastic simulations. The connection to SWE is anything but broken: I am now working on several research projects with Professor Cheng and my academic colleagues at SWE from the industrial side. It's always amazing to see that a number of my students here in industry, who I helped train, are now colleagues of mine - a great feeling and proof of the quality of SWE, which prepares students for success in their future careers.

SWE

Teaching and Alumni
Former students remember their time atSWE

SWE Team with small wind turbine

Denis Matha, a former PhD student, also has fond memories of SWE: "Especially the cooperation with highly motivated and very capable colleagues and an atmosphere in which every single employee is willing to invest time and energy beyond the usual for the success of SWE is, in my opinion, something unique for a university institute."

The time at SWE was excellent preparation for management positions in industry, says Matha: "The high level of personal responsibility and range of tasks we were given was challenging, but definitely very good preparation for future challenges and leadership roles in the industry, compared to many other documentary programs, which are often much more school-like."

Denis Matha successfully initiated the topic of floating wind at SWE in 2009 after a stay at the National Renewable Energy Laboratory in the USA. He is now coordinator of the "Floating Wind" division at the international consulting firm Ramboll.

The new test field on the swabian alb wind energy in mountainous complex terrain

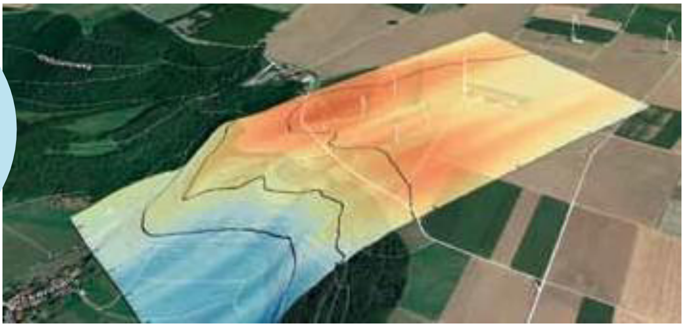
WindForS
old test field

Good research needs good research conditions. Ulrich Hutter, one of the fathers of modern wind power and the founding father of SWE, knew this in 1956 when he opened Germany's first wind power research site on the 734-meter-high Stottener Berg on the edge of the Swabian Alb near Schnittlingen. That was more than 60 years ago.

The Austrian-German wind power pioneer set up the prototype of the legendary StGW-34 wind turbine, which he designed, on the test site near Schnittlingen. The two-bladed wind turbine is considered the forefather of modern free-running wind turbines. Other machines were added later. In 1986, the test field was renamed "Ulrich W. Hutter Test Field" in Hutter's honor. In the years that followed, however, wind energy research stalled more and more. Since 1997, the site has been used primarily for commercial wind energy production.

Since 2004, i.e. since SWE has existed, the call for the revival of a wind energy test field on the Alb has also become louder. The researchers longed for an innovative and modern facility that would serve research purposes especially in the mountainous complex terrain. One thing is clear: the expansion of wind energy in Germany plays a key role in implementing the energy transition. And in order to drive the expansion forward, challenging sites must also be developed, for example in forests or on high and ridge tops. But there is still a lack of knowledge about this.

Visualization of the
future WindForCe
Wind energy test field



Wind energy in
the mountainous
complex
Gel8nde

This knowledge gap now needs to be closed. The project, a special test field for a mountainous complex, is finally taking shape. The year 2017 marked a turning point in wind power research in the Si.iden of the Repu blic: In the fall, the first section of the new test field went into operation. Not far from the old Ulrich Hi.itter test site near Geislingen an der Steige, a state-of-the-art platform is being built for wind energy research in Si.id Germany.

The new test field is a baby of the Wind ForS research cluster, which includes numerous German universities and colleges. The WINSENT project, financed by the BMWi and the state of Baden-Wi.irttemberg, is coordinated by the Center for Solar Energy and Hydrogen Research Baden-Wi.irttemberg, which will also take over the initial operation.

The technical equipment of the test field was designed in the KonTest project in such a way that it ideally serves the preparation, testing and validation of new technologies with regard to materials, construction methods, aerodynamics, load control, load reduction, production technology, operating equipment, measurement technology and monitoring of wind turbines. The test field soil serve both the research and the manufacturers of wind turbines and their suppliers. Landscape aesthetics, acceptance and ecological issues are also part of the research. Furthermore, the concept considers a possible extension of the test field to investigate storage and grid integration of other electric renewable energy sources.

Wind energy in
the mountainous
complex terra8nde

The situation

The test site is located on a high plateau near the so-called Albtrauf, a steeply sloping mountain ridge. Special wind conditions prevail here, which are characterized by high turbulence intensities, accelerations and rapid changes of direction due to the local topography and the steep slope aligned with the main wind direction. These wind conditions, which are typical for complex terrain, place very special demands on the structure, design and operation of wind turbines. Such a test site with the above-mentioned possibilities and equipment features is unique in this form worldwide and stands for the region of southern Germany as a lighthouse project with global appeal.

The measurement infrastructure

A total of four meteorological measuring masts, each 100 meters high, will be erected. They frame the two research wind turbines. In addition, LiDAR systems will be installed both on the ground and on the wind turbines. They measure the wind fields in unprecedented resolution. The measured wind fields can even be used to enable predictive turbine control or to implement wind farm control systems with active wake deflection. Furthermore, measurement drones are used as a swarm. They can fly to any desired point in the measurement field and deliver highly resolved data for turbulence research. Both quadrocopters and airplanes are used. With the use of different measurement techniques, new insights into turbulent wind flow in complex terrain can be gained.

The research wind turbines

The two wind turbines will be so-called glass turbines. That means the researchers will have access to all the details of the turbines, including the control system. They can change or replace any component and then analyze how the machine behaves. The turbines are relatively small, with a rated power of 750 kilowatts and a rotor diameter of 55 meters. The size of the turbine was chosen so that the findings could be transferred to larger wind turbines. The size of the wind turbine makes it possible to replace and test larger components such as rotor blades easily and cost-effectively. In this way, the scientists can explore how special turbines can be designed for low-mountain sites. The result could be

Student excursion

For example, lightweight, separable rotor blades that simplify transport and logistics in the complex area. Likewise, ti.irms that are designed fi.r the special loads.

Access to the control algorithms allows the development of new control strategies to increase performance and yield and extend the structural life of wind turbines. The openness of the research facilities offers component suppliers a manufacturer-independent test platform that allows them to test new technologies. This allows suppliers to accelerate product development and facilitates market entry, especially for medium-sized companies. The bottom line is that the research country will help make wind harvesting more efficient in mountainous and complex regions, thus advancing wind power in general.

Outlook
The future of wind power and renewable energies

Outlook -
Future of wind power and
of renewable energies

Stuttgart is a synonym fi.ir innovative technologies - also in terms of energy. In keeping with tradition, SWE's employees are not resting on their laurels, but are always looking to the future. There is no doubt that many things will change in the energy sector in the coming years. Renewables will play a key role and increasingly replace fossil-fuel power plants. To ensure that the conversion of the power plant park takes place largely without friction losses, SWE researchers are already looking to tomorrow.

Wind measurement mast and lidar
for power curve measurement

Offshore

Wind power ahoy !

Offshore wind measurement with floating lidar device

Wind energy on the high seas is becoming increasingly popular. 1 It's clear that offshore wind farms can generate between 3,500 and 5,000 full-load hours per year - significantly more than at conventional onshore locations. The world's first wind farm went into operation off the Danish island of Vindeby back in 1991. Today, more than 12,000 megawatts of offshore wind power capacity are connected to the grid worldwide. Most of this (88 percent) is located off Europe's coast. The remaining twelve percent is mainly located off China, Japan, South Korea and the USA.

It's a real success story: The costs fi.ir offshore wind power are falling much faster than most experts expected. The industry's target of 100 euros per megawatt hour by 2020 has now been achieved. This is mainly due to the fact that the offshore wind industry has now mastered the risks and greatly optimized the entire value chain. Not to be forgotten are the stable political and financial conditions, which are essential for long-term project planning.

Offshore turbines now mostly have rated outputs of ti.inf to six megawatts. Prototypes are already reaching outputs of ten megawatts. Fi.ir further cost-and even offshore wind power without any subsidies, plant sizes of up to 15 megawatts are expected from 2023. The larger the turbines, the more worthwhile the effort. This is because the construction of offshore wind farms requires complex logistics. Huge cranes and supply ships are needed, as is the right weather window. In addition, there are countless highly trained specialists. The grid connection is also immensely costly and is all the more worthwhile if the wind turbines deliver more electricity - and this is better achieved with powerful wind turbines.

The maintenance of the turbines on the high seas is also an enormous logistical effort. The wind farms are located far out at sea, and the weather often makes it impossible to go out by boat and climb onto the turbines. The risk of injury is too great. There is also the time factor: most offshore wind farms in the German North Sea are located far from the coast, so the transport route via ships is long. For fast and urgent repairs, helicopters are often used, which significantly increase the accessibility of an offshore wind farm. For very large offshore wind farms, it is even worthwhile for the park operator to install special living platforms for the service personnel.

The question of how the plants are anchored to the seabed is also anything but trivial. They stand either on gigantic monopiles, oversized steel pipes that are hammered into the ground, so-called jackets, or gravity foundations that are held in place by their sheer mass alone. But all of these foundation options have a drawback: they require shallow waters, and the water must not be deeper than 50 meters, otherwise the cost is too high and the budget is exceeded. But shallow coastal strips with good wind conditions are rare. They are actually only found off Europe's coasts. This explains why most offshore wind turbines are located in Europe.

For this reason, the focus of offshore wind power has increasingly turned to floating turbines. The world's first floating wind turbine has been drifting in the sea off the coast of Norway since 2009; here the water is 220 meters deep. The floating skimmer is designed as a so-called Spar buoy - a gigantic steel tube that resembles the float of a fishing rod. Steel cables hold it in position.

The pioneer Statoil, which also built the world's first floating wind turbine described above, is currently erecting a 30-megawatt wind farm off the Ki.iste Schott lands. The fi.inf six-megawatt wind turbines are being supplied by Siemens. The company sees itself as a pioneer in floating wind power: Our technology can already be described as pre-commercial. We expect further cost reductions in the area of floating wind turbines, which will drive the expansion," says Michael Hannibal, business fi.inf Offshore Wind at Siemens.

Outlook - Future of wind power and of renewable energies

SWE researchers are working with specialists from other universities to reduce the cost of floating wind power. One option they are considering is to make a float out of concrete instead of expensive steel. The credo: concrete is not only cheaper, but also more ecological and durable. In addition, the production of concrete structures is implemented locally and has positive effects on the local economy.

The Stuttgart researchers are also conducting research on neural networks that record the loads on the structure of wind turbines. The idea behind it: Monitoring the turbine by estimating loads using sensors that are installed on the turbine anyway. With these neural networks, the data can be combined in a meaningful way to provide information about the status of the structure. And what is the use of all this? You can plan maintenance depending on the condition of the plant - and even make it possible to keep the plant running.

In the area of control, robust as well as pradictive control strategies are designed and tested in order to reduce the loads.

reduce - and increase the energy yield. The focus here is on using LiDAR measurements to pre-control the blade angle. An extension of the predictive control is the integration of wave information. This is particularly interesting for floating wind turbines because it allows the movements of the floating body to be reduced. For floating wind turbines, the less the turbine moves, the higher its output and the lower the loads.

Another application of the LiDAR system is wind parking control. The current behind each turbine can be recorded with the LiDAR system. This information can be used to actively influence the wake and increase the efficiency of the wind farm. The Interaction van wake between the individual turbines is very complex, and more research will be needed before wind farm control can actually be deployed. This is good news for the researchers from Stuttgart.

All in all, marine wind power offers enormous potential. Large farms are capable of supplying entire cities. The cost reductions indicate that the price level of offshore wind will be at the level of onshore wind in the foreseeable future, even without subsidies, according to the latest tenders. Most importantly, interconnected offshore wind can provide baseload power and thus increase security of supply.

Baltic | offshore wind farm

Airborne Wind Energy
Wind power takes off

Outlook -
Future of wind power and
of renewable energies

Flying wind turbines that soar to great heights and capture the steady, strong winds there are no pipe dreams. They already exist. The field of airborne wind energy is still young and relatively small, with around 60 companies around the world working in this area. But the prospects for the future are terrific.

Some of these companies already have impressive prototypes in the air. Google, for example, is testing such an airborne wind turbine through its offshoot, Makani. Makani's development resembles a motorized airplane. The carbon-fiber wing is an impressive 28 meters long, weighs over a ton and generates 600 kilowatts. It circles in the sky, much like a flying kite, with its eight propellers and generators harnessing the enormous wind current to produce electricity. A long cable, which also serves as a "wire cord," conducts the electricity to the ground.

In Germany, the companies Enerkite from Brandenburg and Skysails from Hamburg are aiming high and are also testing the first prototypes. The potential of the technology is also evident at the energy provider Eon. Eon has just invested in the Dutch aero-wind company Am pyx Power. The two want to use the foundations and the grid connection of a former offshore wind farm off Ireland. This is certainly a sensible step for scaling up the technology," says Po Wen Cheng.

The advantage of flying power plants is that you don't need a tower and therefore a lot of material, but at the same time you generate more electricity than with conventional wind turbines. They also like to be built higher and higher. Because even the windmullers near the ground know that twice the wind speed equals eight times the energy yield. And the higher you go, the stronger the wind blows. The heights to which airborne wind turbines rise are virtually inaccessible to three-flight pilots on their towers: Up to 400 meters high, some want to go even higher.

Ultimately, however, this is a question of cost optimization, because greater height means higher costs for the cable system that brings the electricity to the ground. After all, the additional energy yield from the height increases more slowly compared to the costs. Where exactly the optimum lies remains a task for research for the time being.

Enerkite flying wind turbine
© Enerkite

Another advantage of airborne wind energy is its deployment flexibility. Conventional wind turbines have to be designed for extreme wind conditions such as tropical storms. This is not a problem with flying systems: they can simply be left on the ground. This has material and financial advantages because extreme conditions can be avoided.

However, flying wind turbines require a lot of space and are therefore mainly suitable for offshore sites or deserted areas. The technology is still quite expensive, but all in all, experts agree, it offers gi gant potential. At some point, flying wind turbines could harvest electricity more favorably than the current wind riiders - and they are already amazingly efficient in good locations.

Fort Felker, former director of the National Wind Technolo gy Center in the U.S. and current Makani team leader at Google X, is a real fan of airborne wind power: "The technology makes it possible to harvest more energy with more powerful turbines." A study by the Fraunhofer Institute for Wind Energy Systems (IWES) in 2013 estimates the price at two to four cents per kilowatt hour, which would make high-altitude wind power more favorable than all known energy generation options. However, the "competition" from conventional wind turbines and photovoltaics is not closing in. In the meantime, the figures of two to four cents per kilowatt hour for these technologies are also within reach. It remains an exciting race among the renewable ener gies.

Therefore, SWE is always looking for new scientific challenges. Within the University of Stuttgart, the expertise for the development of Airborne Wind Energy is available. In addition, there are synergies between the work at SWE and airborne wind energy, for example in the areas of LiDAR measurements, LiDAR control and dynamic simulation. Through the topic of airborne wind, cooperation within the Faculty of Aerospace Engineering can also be strengthened. The concrete goal is difficult to predict for SWE, but as so often before, the attraction lies in discovering and developing new technologies.

Memory
Wind power for slack days

Outlook -
Future of wind power and
of renewable energies

In order for renewables, especially wind power, to be able to take over large parts of our energy supply, storage facilities are needed. In this way, parts of the expensive high-voltage transmission lines can be replaced. At the same time, eco-electricity would flow continuously into the grid.

On the way to a large-scale supply of renewable energies, there is hardly any way around the use of storage systems. Wind and sun simply fluctuate too much to be able to rely on them 100 percent. This does not mean, as is often propagated, that monstrous and extremely expensive storage capacities will have to be built up. But it will not be possible without it. This is reason enough for SWE scientists to address this issue as well.

For longer periods of time, large-scale storage is needed. Pumped storage power plants are the most prominent example of this: When there is a power shortage, water is pumped up to a higher level. When electricity is needed, the water flows downhill and drives turbines. However, especially in Germany, there are hardly any areas left where such storage power plants can be built.

New technologies are therefore under discussion. For example, concrete ball storage. This technology was recently tested in Lake Constance. A three-meter hollow concrete sphere was sunk into 100 meters of water. An empty sphere can be imagined as a voile battery: If you open a valve, water flows in at high pressure and drives a turbine. The trick is that the pressure rises with increasing depth. In real life, the spheres are supposed to be 30 meters grol5 and weigh 20,000 firs. They are to deliver an output of ti.inf megawatts. Installed at a depth of 700 meters, they could store 20 megawatt hours of electricity. Fi.er the North Sea and Baltic Sea, they are thus not suitable, the water is simply too shallow. The Mediterranean, on the other hand, is predestined: In combination with offshore wind farms, this creates reliable large-scale power plants. But as a long-term

This Li:isung is probably unsuitable as a large wind turbine with ten megawatts of power can recharge such a storage unit within two hours.

Outlook -
The future of wind power
and renewable energies

Wind and water also form an excellent combination on land: This is shown by the example of "natural storage" in Gaildorf in southern Germany. There, wind power and pumped storage are already forming a future-oriented symbiosis. The bases of four wind turbines, which are being built on a mountain ridge, are simultaneously designed as water reservoirs. They are connected via pipelines to a power plant and an associated lower basin 200 meters down in the Tai. The storage soil will rise and fall quickly to provide balancing power to stabilize the power grid. Researchers are also considering how to make use of the numerous disused mines in Germany. Their idea is to seal the galleries and convert them into lower basins for pumped-storage plants.

Siemens and its partners are currently testing a "holy" storage technology in Hamburg: A pile of stones is to be heated to 600 degrees by a gigantic fohn using excess electricity. When electricity is needed, air filters suck the heat back out and direct it onto turbine blades. In the commercial phase, the scientists then plan to scoop up enormous piles of stones. Or better yet, to use existing ones: The slag in decommissioned coal-fired power plants is just the thing. The entire infrastructure is already in place.

The list of potential storage solutions is long. The question of which of the technologies is promising and affordable is difficult to answer. So far, we simply know too little about the requirements and needs. A central part of the research at SWE and in the WindForS network is therefore to investigate all these questions and to research them in a network. The goal is to find out what storage needs exist in the first place. The research involves a wide range of factors, from weather forecasts and yield forecasts for the respective location, to smart-grid solutions and demand-driven control of consumption, to solutions that incorporate both the heat and mobility aspects of people's lives. Experts refer to this as sector coupling.

One of the key questions is how to redistribute electricity to other sectors. For example, to the mobility and heat sectors. One answer could be: Hydrogen. Water mole-

Coupling
electromobility
with energy
storage
Wind energy

The hydrogen is stored in an electrolyzer, where it is split into hydrogen and oxygen using eco-electricity. In vehicles or buildings, the hydrogen can then be converted into heat or electricity for electric motors in fuel cells.

A more direct variant is aerothermal energy. In this case, the energy generated by a wind turbine, for example, is converted directly into heat, for example via a hydraulic system. The advantage of such a system is that conversion losses due to the generator and downstream processes are eliminated. However, this presupposes that the heat consumers are on site. Industrial plants, nurseries or housing estates are ideal candidates.

In order to be able to fundamentally research such and other future storage scenarios, the WindForS test field on the Schwiibische Alb will be designed in such a way that various storage solutions can be integrated. Here, the expertise of WindForS partner ZSW, the pioneer of power-to-gas technology, represents an important contribution to the implementation of the German government's energy concept.

The goal is ambitious: by 2050, at least 80 percent of our energy should come from renewable sources. The generational energy transition project and the lofty goal of halting climate change is a mammoth task - but one that will secure the future of our children and grandchildren.

Base load capability
How do renewables become reliable biggies?

In the course of the expansion of renewable energies, one term repeatedly comes up as a point of criticism: the lack of base load capability. In electricity supply, this refers to the power that is in constant demand around the clock. In Germany, this amounts to almost two billion kilowatt hours per day. By way of comparison, a large wind turbine produces around 80,000 kilowatt hours a day under good conditions. Even a medium-sized nuclear power plant only produces around 30 million kilowatt hours. So it takes a lot of power suppliers.

Volatility is indeed a shortcoming of renewables, especially wind power and photovoltaics - when the sun shines or the wind blows, a lot of electricity flows. And vice versa. This fluctuation makes it difficult to integrate wind and solar into the electricity mix. Although weather forecasts are now quite reliable, so we know fairly precisely when and how much electricity to expect, short-term fluctuations, such as when a cloud field passes over a large PV system, are unavoidable. So are longer periods without wind and sun.

This means: Wind and solar have only limited base-load capability. But at the same time, it is true that as the share of renewables in power generation increases, the need for traditional base-load power plants decreases. Furthermore, the requirement profile is also changing: It will soon no longer be a question of covering a fixed base load, but of supplementing sun and wind flexibly and reliably in order to cover the demand for electricity. Geothermal energy, hydropower and biogas are good helpers here.
- Their output can be adjusted quite precisely. And in combination, the various types of eco-power plants can then deliver guaranteed quantities. In this respect, renewable energies also have a certain base load capability, but only for limited periods of time. Overall, therefore, there is no way around storage facilities.

Nevertheless, there are numerous solutions that reduce the need for storage. To implement the energy turnaround - the German government has set the course: 80 percent renewables by 2050. Gas-fired power plants can help out, especially with peak loads, but only make sense if the fuel is generated regeneratively. Experts refer to this as "power to gas. In an electrolysis process, okoelectricity can be used to produce hydrogen, which in turn can be converted into methane. The result is natural gas. As is well known, natural gas is easy to store and the entire infrastructure - pipelines, power plants, etc. - is already in place. - is already in place. The first test plants have already been built. The Center for Solar Energy and Hydrogen Research in Baden-Wurttemberg is working on this topic in detail and has already had many successes. In Wyhlen on the Rhine, a plant is to be built that converts hydropower into gas. It is planned to operate an industrial one-megawatt plant for the production of regenerative hydrogen (eH2), which can be used as fuel to power fuel cell vehicles.

Some scientists want to solve the baseload problem with innovative wind turbines: with a very high capa citate factor. In simple terms, this describes the capacity of the turbines and is calculated by dividing the annual energy yield in kilowatt hours by the product of the turbine's rated output multiplied by the 8,760 hours of the year. Very tall turbines with particularly long blades yield especially high capacity factors. Such wind turbines naturally capture more wind and deliver their electricity more evenly to the grid.

But to supply large parts of Europe, it is not enough to optimize individual power plants. The motto here is: think big. Many eco-power plants distributed throughout Europe increase the security of supply. Somewhere the sun is always shining and somewhere the wind is always blowing. In addition, there are technical and economic instruments that can be used to actively control the consumer. Such measures can include energy efficiency, demand response, and daily or hourly electricity price adjustments that encourage consumers to adjust their consumption to the production pattern of renewable energies. It is clear that in the energy world, too, there are many ways to reach a goal.

Wind farms as power plants
The requirements change - an industry comes of age

Outlook -
The future of wind power and renewable energies

Wind farms should behave like fossil power plants. They should supply reliable electricity around the clock. This requirement can best be met at sea with gigantic wind farms. Far out at sea, far from the coast, the winds are almost always strong and persistent.

The larger the wind farms are and the more widely they are distributed geographically, the greater the chance that they will reliably supply us with electricity. This is because large-scale lulls that extend from the Atlantic to the Baltic Sea are rare. But they do happen. The so-called "cold dark doldrums" are the bugbear. The term was introduced in a 2017 study. It refers to a situation in which, on the one hand, little electricity is generated from wind and solar power due to lulls and darkness, but there is a particularly high demand for electricity due to cold climatic conditions. Typically, this case occurs in January and/or February.

In order for the wind industry to be able to supply base-load electricity at all times, the farms must be branched out as much as possible and well connected. This requires a large pan-European network that brings the farms and consumers together. The grid operator TenneT has a first idea of how something like this could look: It wanted to protect artificial islands in the North Sea and collect the electricity from numerous offshore wind farms. Such an island would be six square kilometers in size and serve as a distribution and hub in the European power grid. The Netherlands, Great Britain, Belgium, Norway, Germany and Denmark are paying for TenneT to do this. However, it is not yet clear when and whether this project will be realized.

left side:
Triple Spar concept for floating wind turbines

As you can see, wind power is growing up and has to face the challenges. If it were up to the energy companies and wind turbine manufacturers, we would probably have had significantly more wind farms at sea for a long time. But grid expansion is lagging behind. It is the classic bottleneck, the much-vaunted bottleneck.

Power transmission
How does the electricity get into the socket?

In order to transport the electricity from all the wind turbines, which are mainly located in the far north of the country or even offshore, to consumers in the Si.iden with low losses, new long-distance transmission lines must be built urgently. The same applies to photovoltaics, which are concentrated in Germany's south.
Without grid expansion, there can be no expansion of renewables," is how Po Wen Cheng sums it up.

However, since overhead lines hardly stand a chance due to their low acceptance, immense impact on nature and high losses, new solutions are needed. Currently, the so-called high-voltage direct-current transmission, or HGO for short, is favored. These lines are laid underground. They are less disruptive to the landscape, which increases acceptance. HGU lines operate at extremely high voltages of 500,000 or more volts. This reduces losses. In China, lines have already been built that operate at an incredible 1000 kilovolts - that's a million volts anddistances of several thousand kilometers i.iberbri.icken.

The Si.idlink project, a power line running from Brokdorf in the north to near Schweinfurt in Si.id Germany, uses an HGU line. The first section could be completed in 2024. However, laying HGU lines is anything but minimally invasive: Since the individual cables are heils, they have to be laid with large distances in the ground. Wide routes also have to be created - in other words, aisles have to be cut in forests.

More elegant are the so-called superconductors. These operate virtually loss-free and can transport enormous amounts of current with small cable cross-sections.

Superconductivity occurs only in certain materials. The magnesium diboride (Mg82), which was only discovered in 2001, is promising. Such materials lose superconductivity below a charact-

Wind energy expansion and power grid expansion must be driven forward at the same time. become

ristic temperature their resistance. Depending on the material, this effect occurs between minus 273 and minus 143 degrees Celsius. For the lines to achieve this effect, they must be cooled regularly. For long-distance pipelines, therefore, ki.lter regulator stations must be installed regularly - comparable to the compressor stations in natural gas pipelines.

Nevertheless, the technology is not entirely new. Superconducting power cables have been in use for a long time, for example in medical imaging (magnetic resonance imaging, MRI) or in generators and particle accelerators.

In some cases, the cables can even be laid in existing conductors. But because superconductors are extremely expensive, they are particularly suitable for distributing electricity in urban areas. So far, however, there are only pilot plants. After all, a one-kilometer cable is already in place in Essen. In the future, this technology could be used increasingly - and give renewables, especially wind power, a greater role.

Outlook -
Future of wind power and of renewable energies

Grid expansion is happening not only at the high-voltage level to transport offshore wind power from north to si.iden, but also at the low-voltage level. Most photovoltaic systems on roofs feed into the low-voltage grid, and when the weather is sunny, a bottleneck is created here as well, because in the good old ener gy world, the distribution grid was only fi.er to distribute electricity, not fi.er to collect it. By installing solar panels, every homeowner becomes not only an energy consumer, but also an energy producer.

Ultimately, the number of decentralized energy producers makes the energy system more complex. But Stuttgart is also aware of this trend: It is an important topic within the WindForS research network.

The shifting of loads could also help to relieve the grids in extreme situations and thus save the construction of expensive transmission lines. Experts refer to this as sector coupling. For example, electric cars could be refueled at night, refrigerators could be cooled down more at night and "thawed out" during the day, and energy-intensive industries could carry out their work when there is plenty of electricity and call on less load during periods of low electricity. However, all this presupposes the much-discussed "smart grid" - a digital power grid that always knows how much energy is needed and how much is available. And then also controls who gets allocated how much power.

right side:
Prototype of a floating wind turbine developed in the EU project FLOATGEN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Closing words
by Chair Po Wen Cheng

What's next after ten successful years of the SWE Endowed Chair? And how will wind energy develop over the next 20 years?

History has taught us that humans are not particularly good at making predictions about the future. This is because uncertainties in complex systems are very large and developments depend on many factors. Nevertheless, it is possible to form a picture of the future on the basis of trends and current developments. That is what I will try to do.

Windy and sunny future

In order to make a statement about the future of wind energy, we must first consider the future of energy itself. Since the Paris Climate Agreement, it is clear that our energy system must gradually be converted to renewable energy. Until recently, renewable energy was seen as a kind of toy or luxury of industrialized and economically rich countries. This was mainly due to the fact that the energy production costs of renewable energies were higher than those of conventional energy systems. But that has changed. The rapidly falling costs of wind energy and photovoltaics have helped them become more economically competitive, even without government subsidies. In sunny countries, electricity from photovoltaics is already available for less than three euro cents. The cost of offshore wind is also falling much faster than expected. For the year 2023, offshore wind power has been offered for the longest time, without any subsidy. In this case, the operator of the wind farm receives only the price offered on the electricity market. We must not forget: We are talking about prices that were unthinkable until a few years ago! This has now also increasingly led developing countries to rely more and more on wind power and photovoltaics as a real source of energy.

Closing words by Chair Po Wen Cheng

alternatives to coal and gas. And not only because they are better for the environment, but because renewable energies are simply more economical.

Wind energy and photovoltaics have benefited most from the growing global market for renewable energies. Because of standardized production and modular design, components and systems can be manufactured at ever lower cost. And the larger the market becomes, the faster prices fall. In most countries, wind power and photovoltaics together will account for the majority of renewable electricity. This dominant role will become more entrenched in the future the faster costs fall, which is taken for granted by all sides.

The questions we ask ourselves are: How fast can the market grow and how fast will costs fall? The two questions cannot be answered separately, as one reinforces the other. Moderate growth is expected in highly developed markets, as energy demand increases more slowly or even decreases. In developing countries, on the other hand, markets are growing rapidly. This is mainly due to rising energy consumption and high population growth. The rate of growth, in turn, depends very much on the policies and conditions of each market. At the moment, after the Paris climate agreement, one can speak of a tendency to positive development, which continues to speak for a fast growing market in wind energy and photovoltaics. Another factor that has led to rapid cost reductions of both energy sources is the shift from fixed feed-in tariff to tendering. In general, it can be said that tendering as a market t instrument has achieved its goal of reducing costs more quickly through competition. At the same time, this means that the uncertainties and risks for investors have increased. This can lead to lower growth in the short term, before investors have come to terms with the new market conditions.

Sector coupling

Another factor that can influence the growth of wind and photovoltaics is the coupling with other sectors. Until now, wind energy and photovoltaics have only played an important role in electricity. This may change significantly in the coming decades. The electrification of mobility is rolling

The situation is unstoppable: due to the loss of confidence, above all because of the emission characteristics of combustion engines, and due to political considerations to ban combustion engines altogether in the future. An important stimulus here could be China - the world's most important car market If China bans the internal combustion engine, others will follow suit. It is undeniable that this decision has political, economic and environmental facets. The direct impact will be the accelerated transition to electromobility - and the increased demand for electricity.

Closing words by Chair Po Wen Cheng

The coupling with electric mobility also brings advantages for wind and solar energy by reducing the variability of power generation by the batteries in the electric vehicles. In addition, electric vehicles require green power from wind and solar energy in order to be better off than vehicles with internal combustion engines.

Coupling with other sectors is also desired if renewables are to make energy consumption more sustainable. Electrification of energy consumption can increase energy efficiency, since conversion of electrical energy into useful work can be very efficient compared to systems based on fossil energy. In addition, active control of energy consumption in the form of heat and work can mitigate the effects of variable power generation.

In summary, it can be said that the growth of wind energy and photovoltaics will continue in the coming decades. However, no one can say with any certainty how high the growth rate will be, since the influencing factors are many and varied.

Versatility of wind energy

Onshore and offshore wind energy are growing more and more apart, as the requirements are very different. In order to meet cost reduction targets, larger and larger turbines will be required. Ten-megawatt wind turbines are already on the doorstep, and 15-MW turbines are hardly considered a pipe dream anymore. The question is, how big can an offshore turbine get? No one can clearly state the exact value at present. What is clear, however, is that an increasingly large wind turbine poses new challenges for the wind energy industry.

Professor h.c. Schlecht,
Professor Gasch
and Professor KUhn
at the SWE Symposium

manufacturing of components, logistics, and installation. The cost savings from fewer facilities, foundations, transportation and installation operations are offset by more expensive individual facilities, higher mobilization costs for more efficient vessels, to name just a few criteria. The cost optimum is a compromise between often conflicting criteria, and may shift due to technological advances as well as the increased availability of installation vessels.

Within offshore wind energy, the development of floating wind turbines is interesting for the future. It opens up new locations with large water depths that are too uneconomical for ground-based foundations. This is less relevant for the North Sea, where there are sufficient sites with shallow water depths, up to about 50 meters. For many other countries, however, floating foundations could significantly increase the potential of offshore wind energy. Technically, it is safe to say that floating wind turbines are feasible with today's technology. The biggest challenge is the cost reduction required to make floating wind farms economically viable. Research can help the industry understand the behavior of floating turbines in a wide range of environmental conditions, for example, by actively controlling turbine behavior through predictive control. Likewise, methods can be developed to determine the structure of individual sites.

optimize. One thing can already be predicted today: The cost reduction effects can only be significant if corresponding market sizes are available. Here, active market control for floating wind is necessary to set the cost reduction in motion. There is much to be learned from the developments in offshore wind energy, where cost reduction targets have been achieved in a very short time. With competitive costs for floating wind, the entire offshore market can grow even stronger and create synergy effects for offshore wind energy with ground-based grids.

The trend in onshore wind turbines is also toward larger machines. Onshore, relatively large rotor diameters of 140 to 150 meters are currently being used, with relatively small generators of four to ti.inf megawatts. This is due to the higher energy yield at lower wind speeds. This allows the capacity factor to be increased significantly. A higher capacity factor, in turn, improves the economic viability of using wind energy at low-wind sites. The issue of acceptance is also becoming increasingly important, as the perception in the landscape is significantly increased in view of the i.iber 200 meters of the turbines. Ultimately, it is a question of preference. Because larger turbines mean fewer turbines. At the moment, there are over 27,000 wind turbines on the grid in Germany. If all these turbines were replaced by modern megawatt turbines, we would have over 100 gigawatts of installed capacity.
- we don't even have half of that: at the end of 2016, only 45,910 megawatts were connected to the grid nationwide.

So what does the distant future hold for wind energy? Will wind turbines continue today's development trend and simply get bigger and taller, or can something truly new still emerge to replace the wind turbine as we know it today?

Of course, no one can predict that with certainty. Today's concept: three rotor blades rotating on the side facing away from the wind, horizontal axis of rotation, variable speed with pitch control, is very successful because the engineers have improved the concept again and again over the years. This has been done in terms of efficiency and scalability as well as in terms of manufacturing processes, so that other competing concepts have had little chance of success. A well-known example is the vertical axle. The

Closing words
by Chair Po Wen
Cheng

Wave tank test
in the Triple
Spar project

The production chain for the current concept is designed for cost efficiency, and a competing concept must first achieve this cost reduction. This is hardly possible without high sti.ick numbers.

Does that mean that nothing new can be created with wind energy? No, of course not. A remote possibility is flying wind power plants based on large kites. Here we are dealing with a radically new system. A system where high cost savings are possible. Material requirements can be much lower than for a conventional wind turbine. At the same time, of course, there are a lot of challenges that need to be overcome before airborne wind power can be recognized as a real alternative to the wind power concept that is in place today. This will not happen in the next five years, but will require 15 to 25 years of intensive research and development. It is important to remember that the bar is set very high for the energy production costs of wind turbines. This in turn means that any challenger will be measured against this yardstick. As we all know, nothing is impossible, but any new technology will definitely have to prove that it offers safer and more cost-effective power generation than the good old wind turbine.

Closing words
by Chair Po Wen
Cheng

Role of SWE - what does the chair need to change to still be at the forefront of wind energy research in 20 years?

As a researcher, you have to identify technology trends early and exploit the potential through research. Offshore wind energy, LiDAR technology for wind measurement and predictive control, and floating wind turbines are good examples from the past 20 years at SWE. With LiDAR and floating wind turbines, there are still many open research questions that need to be answered. How can LiDAR be used to more accurately determine turbulence, wind shear, and three-dimensional wind speed? For floating wind turbines, there are new challenges related to the control of the turbine to reduce the movement of the floating foundation. The wake of floating wind turbines and their influence on the loads of neighboring turbines are not well known, as there is no wind farm with floating turbines yet. In the future, SWE would like to continue to work intensively on these two topics and, building on the previous work, to make an international name for itself in this area.

One of the strengths of the wind energy chair is its close cooperation with industry. This means that the research topics are strongly oriented to the application. This in turn creates synergies between research and application, but at the same time there is a risk of being quickly overtaken by industry because the lead on the research side is not sufficiently large. For this reason, we need to look at longer-term prospects for the future. For example: What could wind energy use look like in 20 years? Which technologies could push forward that are still considered uneconomical today? Technologies that offer potential for certain applications but have not yet been able to establish themselves due to cost reasons. Ich den ke, for example, on two-blade wind turbines, vertical lasers or tidal current machines. SWE has already been working intensively on some of these topics. After all, research should not only be based on the direct economic cost-benefit calculation, but also on the gain in knowledge and the courage to innovate. Without the necessary scientific knowledge, no statement can be made about economic viability. And without the courage to innovate, only incremental improvements will be achieved.

sion. For this reason, we at SWE will continue to work on topics that are generally regarded as high-risk, but which offer great technical potential. One of these ideas could be airborne wind energy. This technology could revolutionize wind power in the future, but it could just as easily crash in the near future due to technical developments or other conditions.

Closing words
by Chair Po Wen
Cheng

The task of research at SWE should be to forge sy nergies with existing wind energy research and to incorporate expertise from research areas within the Institute and the Faculty of Aerospace Engineering. These may include, for example, aircraft design, lightweight construction, aerodynamics, and flight control. It will not be an easy task to build a dedicated platform, but without ri siko there will be no innovation.

In the future, the interaction of different components of the energy system **will become** increasingly important. At the beginning of wind energy development, a lot of attention was paid to components such as the tower, generator, blade, etc.. Then the wind turbine started to be considered as a system, the interaction between the different components and the control system as well as the interaction between turbulent wind flow and the whole system. This system orientation also extends to the wind farm. It makes sense to model a wind farm as a whole in order to capture the interactions between the individual turbines.

In the future, the system concept will become more important. The more decentralized energy systems are connected to the grid, the more complex the overall system will become. In addition, consumers will demand more flexibility and have higher requirements, for example through the intelligent control of appliances or increased power requirements for charging electric vehicles. The ultimate goal could be "Dispatchable Renewable Energy" - renewable energy generation that is always on demand through system integration of different technologies. This does not always have to be linked to energy storage, but rather to finding innovative solutions that represent an economic optimum for the system and at the same time ensure the reliability requirement for the energy supply.

Closing words
by Chair Po Wen
Cheng

So what is the role of the SWE?

The role of a chair is not only to conduct research, but also to provide quality education to students. It is a continuous process to constantly improve the ouality of engineering education by incorporating research projects and not losing sight of the practical relevance of the teaching content. The requirements for graduates change with social change and digitization. It is the task of every educational institution to prepare students for the demands of a digital society and equip them with the necessary skills. This includes not only specialist knowledge, but also the ability to deal critically with new technologies. After all, new technologies usually bring with them moral and ethical issues and implications that are often neglected by Inge nieurs. Our goal is not to create servants for industry, but to challenge critical thinkers with new ideas and thus help shape the future of society.

Through the ten-year foundation period, the Karl Schlecht Foundation has created a sustainable basis fi.ir for wind energy research in Si.iddeutschland. The early years were not always easy and the challenges for the future are still an issue for both research and teaching. Nevertheless, we look to the future with confidence.

We would like to take this opportunity to thank the University of Stuttgart and the Karl Schlecht Foundation for their continuous support of students and staff. We would also like to emphasize the merits of my predecessor Prof. Martin Ki.ihn and his commitment during the establishment of the chair. We are also grateful for the financial support of our research projects from the state and federal ministries, the European Union and our industrial partners. We are convinced that wind energy, which has a long tradition in Stuttgart, can continue to contribute to a sustainable energy supply and thus to a better world for future generations.

Fig. back: Wind measurement in complex terrain with different measuring techniques

The Stuttgart Chair for Wind Energy (SWE) is anchored as a chair at the Institute of Aeronautical Engineering of the Faculty of Aerospace Engineering and Geodesy at the University of Stuttgart. The SWE is the first university chair for wind energy in Germany, was founded in 2004 and is based on an endowment from Dipl.-Ing. Karl Schlecht, founder of Putzmeister AG, Aichtal. Through cooperation within the university, with companies, university as well as research institutions, the use of wind energy and other renewable energy sources is actively promoted. Prof. Po Wen Cheng has been head of the department since 2011. In research, SWE focuses on the system understanding of wind turbines. The overarching research goals are to increase the reliability and further reduce the energy generation costs of turbines that feed wind power into the international interconnected electrical grid.

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