Vast amounts of energy circulate in the earth system: Winds such as this typhoon over Japan reflect a total of 1,000 terawatts of power that drives the world's atmospheric motion.

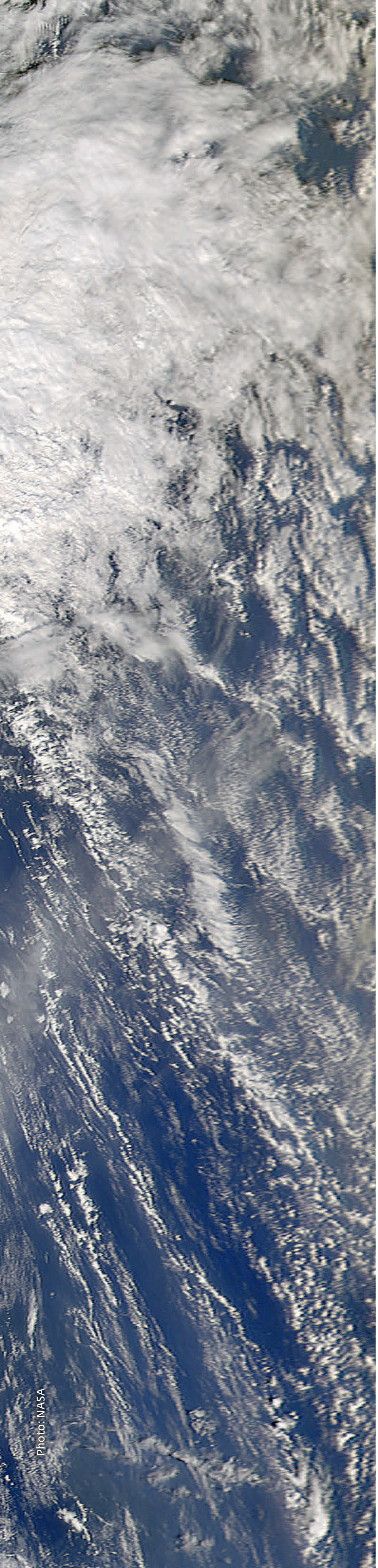


Photo: NASA

Powerhouse **Earth**

Our planet is at work: The sun drives the wind, the waves and the water cycle. Plants store the energy from light in sugar, supplying the fuel of life. Geothermal forces knead the earth, while the moon and the sun primarily keep the oceans in motion. **Axel Kleidon** and his team at the **Max Planck Institute for Biogeochemistry** in Jena are investigating how much energy flows in these processes and how much of this could be used on a sustainable basis in order to satisfy mankind's energy needs.

TEXT **ROLAND WENGENMAYR**

When you talk to Axel Kleidon in his office in the round glass tower of the Max Planck Institute for Biogeochemistry, you end up talking about aliens at some point. And one question quickly surfaces: What would extraterrestrial astronomers be able to observe through their instruments if they pointed them at earth? Would they recognize that there is life pulsating on this small blue planet? Kleidon has no doubts: "They would need only to discover that both oxygen and methane are present simultaneously in the earth's atmosphere."

Back in the 1960s, British scientist James Lovelock already came up with the idea that free oxygen in a planet's atmosphere was an unequivocal fingerprint of life, as the aggressive oxygen reacts chemically with many substances in the environment. These include methane, which is known to even burn in air. If life on earth were to go on strike, the oxygen would disappear from our air; however, the carbon dioxide content would be considerably higher. The atmosphere would then have slid into a chemical equilibrium in which not much happens.

LIFE BRINGS THE ATMOSPHERE OUT OF EQUILIBRIUM

Such an earth would be a barren, lifeless wasteland, like that on our inhospitable neighboring planets. The thin, cold atmosphere surrounding Mars and the oppressive greenhouse hell on Venus consist almost solely of carbon dioxide. This gas is chemically so inert that the composition of such an atmosphere hardly changes at all. Not without life, in any case. >

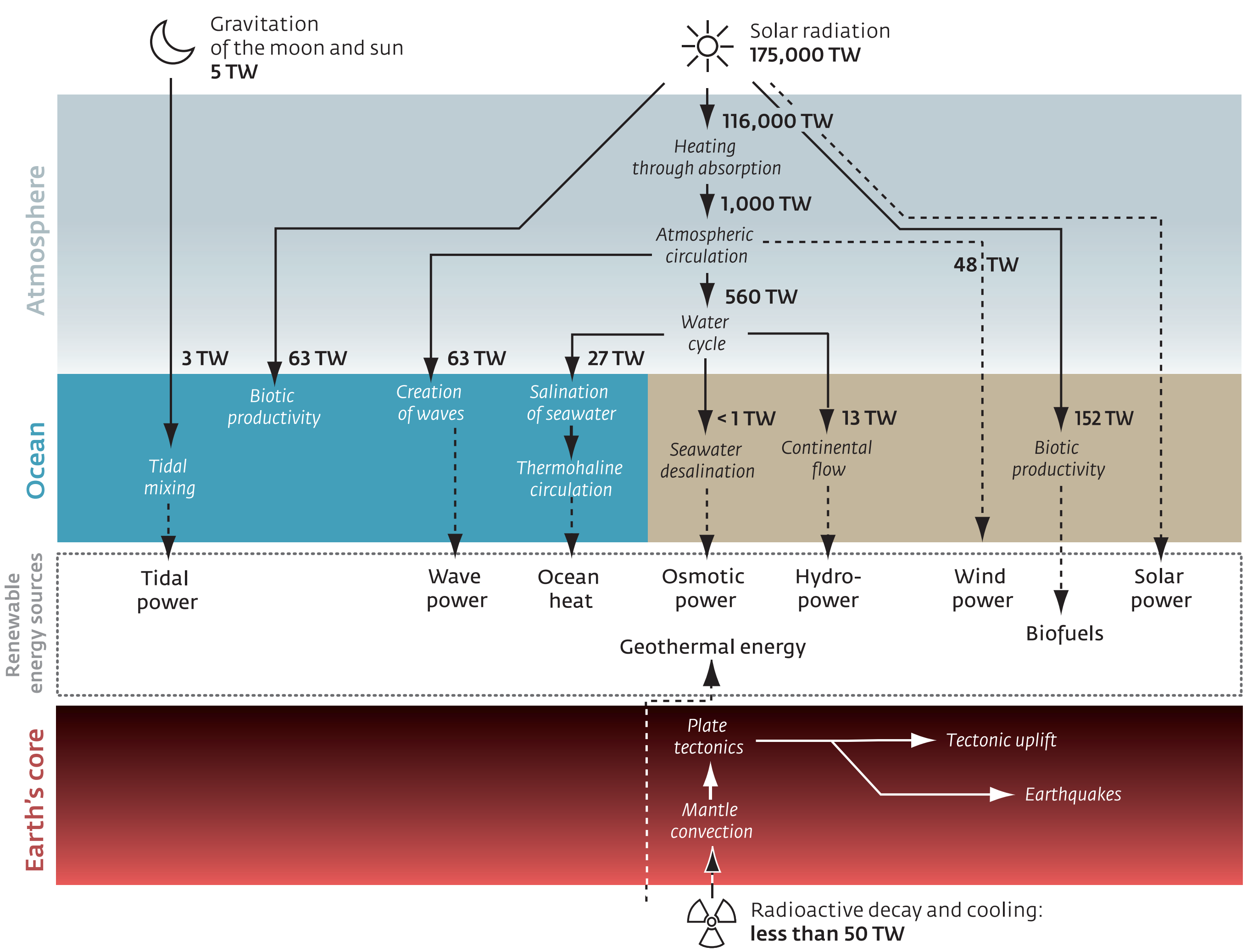
"So it's characteristic for life that the chemical composition of the atmosphere isn't in equilibrium," says Kleidon. Plant photosynthesis continuously drives a global material cycle. It keeps the oxygen content of our air stable at 21 percent and removes excess carbon dioxide from it.

BIOLOGY IMPACTS GEOCHEMISTRY AND GEOLOGY

Living organisms also massively reshape the surface of the earth. Kleidon points through the window to the hilly countryside beyond. "This is the famous Jena muschelkalk, which was produced biologically and stores a large amount of carbon dioxide." Here, in an ancient ocean, the fossil organisms created a huge layer of limestone over millions of years. This occurred in a food chain that started with algae – so, once again, plant life. This gigantic reorganization of entire landscapes by living organisms continues today.

Biology determines the chemistry and the geology of our planet in an extremely active and highly visible way. The name of Kleidon's field of expertise, biogeochemistry, also reflects the fact that living matter and dead matter are closely interlinked on planet earth. However, his team digs around, not in the prehistoric sea bed surrounding them, but rather in computer-based data mines. Axel Kleidon is a theoretician, and he and his Max Planck junior research group investigate the entire "earth system."

For the researchers, this is the totality of all important climatic, geological and biological processes, including all important cycles in the atmosphere, on the earth's surface and below ground. These cycles, which also include photosynthetic biomass production, are closely interconnected. Kleidon is particularly interested in learning what kind of energy drives these processes, and from which key sources this driving energy originates.



The earth system from an energetic perspective: The sun radiates 175,000 terawatts (TW) onto the earth, geothermal energy provides 50 terawatts, the gravitation of the moon and the sun, 5. The diagram illustrates which processes are driven by the energy and how the energy flows can be used.

Graphic: MPI for Biogeochemistry

The Jena-based scientists also use the complex models of climate research. But, as Axel Kleidon says, he loves to condense the core processes that are taken into account in the complex simulations into simple models. For these, he requires only pencil and paper – or the blackboard.

Perhaps his propensity for simple, yet surprising and profound thoughts comes from the fact that he has in-depth insight into numerous scientific disciplines. He studied physics in Hamburg and later at Purdue University in Indiana – plus mathematics and meteorology. After several years as a scientist at Stanford University and the University of Maryland, he arrived in Jena in 2006.

EARTH RESEMBLES A HEAT ENGINE

When the Max Planck scientist explains how he sees the earth system on the whole, a famous scene from a movie comes to mind: the physics teacher, Bömmel, introducing his students to the workings of the steam engine in the German film classic *Die Feuerzangenbowle* (The Punch Bowl). The question as to whether Kleidon also considers earth to be a steam engine makes him laugh. He says yes, but adds, more precisely, that he treats the earth system as a so-called heat engine – the general case of steam engine and combustion engine.

This isn't the only way he views earth, but it provides surprising results. In explaining why this is a scientifically sound procedure, we go on a long imaginary journey that takes us from the sun's radiation to the playroom of Kleidon's son. Eventually we arrive at the question of how much renewable energy the earth system can sustainably provide.

We start at the sun. Its radiation is the earth's main energy source, with a power capacity totaling an enormous 175,000 terawatts. One terawatt is 1,000 billion watts. The heat that rises from earth's interior and manages to move entire continental plates, shaking the earth with earthquakes and causing volcanoes to erupt, is the second largest engine in the earth system, but supplies only around one 3,500th of the energy: it feeds from the decay of natural radioactive elements and the slow cooling and solidifying of the earth's liquid core and supplies around 50 terawatts.

It is useful to compare this with the constant flow of primary energy that mankind as a whole consumes. "This is currently around 16 terawatts," says Axel Kleidon. Thus, for this continuous kneading process, the earth requires only around three times the power that the human race today consumes – albeit it in different forms – as primary energy. Talking to Kleidon gives one a completely new sense of just how energy-hungry our species is.

The tides are a further source of energy. When the moon and sun pull at the earth, their gravitational forces pump energy into our planet, albeit relatively little, corresponding to sustained power of five terawatts.

If the earth is seen as a "steam engine" – or more precisely a heat engine – geothermal heat and tides can safely be ignored. This leaves a pure radiation balance as the earth system's main driver. On the one side of the balance is the radiation from the sun; on the other, the energy re-radiated by earth into space. This ultimately gets rid of the solar energy.

These two rates of energy must be in balance, otherwise our planet would become hotter and hotter, or colder and colder. But wait a minute, the layperson might think: Surely the earth system consumes energy? The wind, waves, hydrologic cycle, plants – all are ultimately driven by sunlight and take a piece of the solar energy cake. The earth must thus absorb more energy than it emits? Wrong! All players in the earth system continuously convert the energy flowing through it from one form into another. The total energy remains constant. At the end of the complex chain, only pure heat energy remains. And the earth radiates this back into space again, just like the radiator of a car engine.

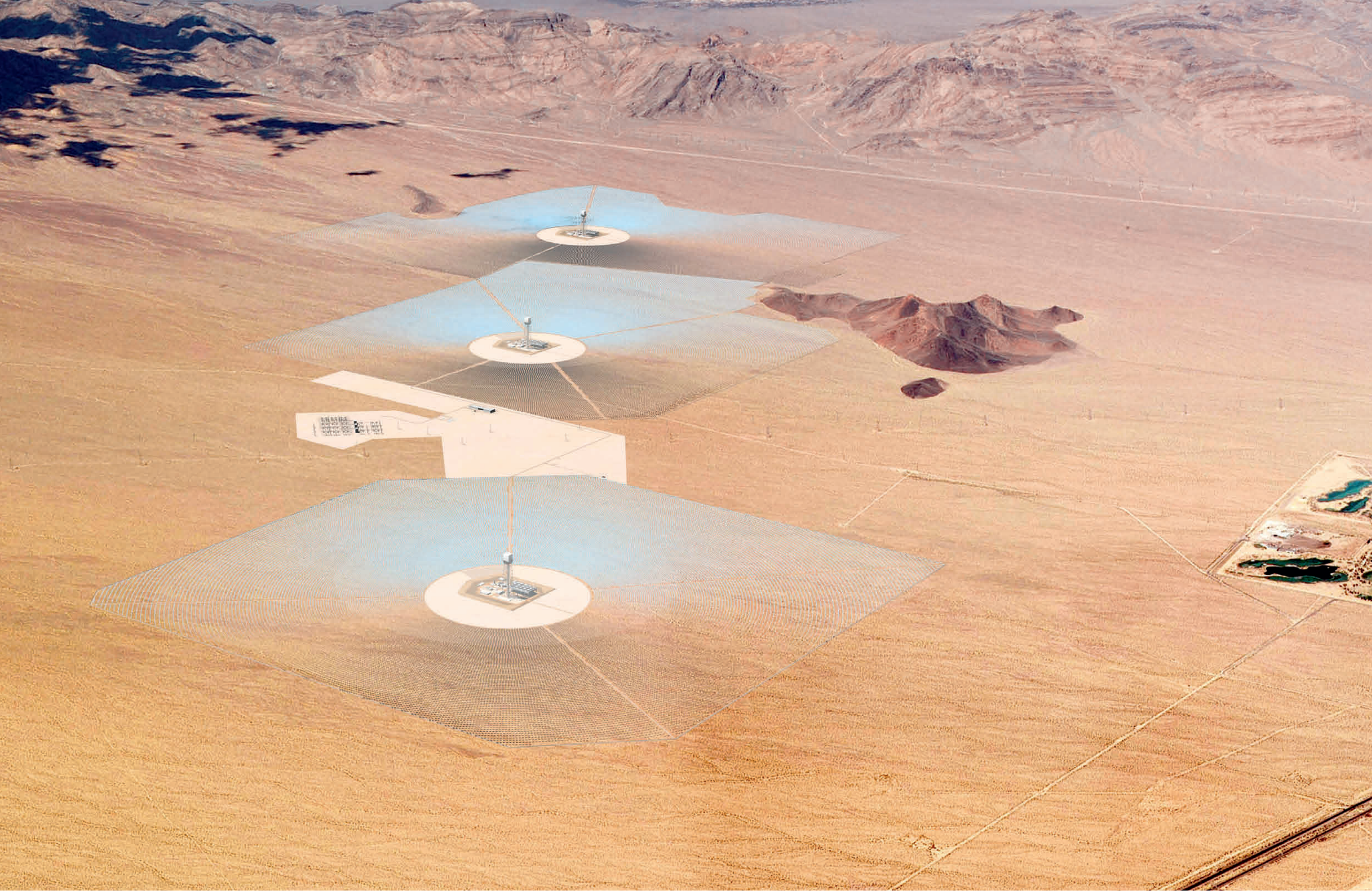
The driving force behind the earth system is thus the conversion of the radiant solar energy into other energy forms. This energy reaches the earth as radiation with relatively short wave-

Observes the earth from an unusual perspective: Axel Kleidon investigates the energy flows in the earth system.

lengths corresponding to a temperature at the sun's surface of around 5,500 degrees Celsius. The re-radiation from the earth into space has much longer wavelengths and is much colder: minus 18 degrees. In between, the solar energy has driven life on earth by photosynthesis – like a complex transmission unit that shifts thermal processes down a gear, as it were.

And this is exactly why the image of the heat engine is so apt. A steam engine also has a hot energy source, namely the fire in the boiler that produces steam. This performs mechanical work, but ultimately has to be cooled and condensed back to water again. The cooling process corresponds to the re-radiation from earth into space. In order to be able to work, all heat engines require a hot reservoir for the energy input and a cold reservoir to dispose of the heat. This applies to combustion engines and power plant turbines alike. >

Photo: MPI for Biogeochemistry – Rudolf K. Wernicke



It is particularly sensible to collect solar energy in deserts. The Ivanpah power plant (above) which is shown here as a model and is being built in California's Mojave Desert, is set to supply almost 400 megawatts of power starting in 2013. In many places, however – for instance in the Erlasee solar park in northern Bavaria (right) – photovoltaics competes with photosynthesis, which uses sunlight to produce biomass.

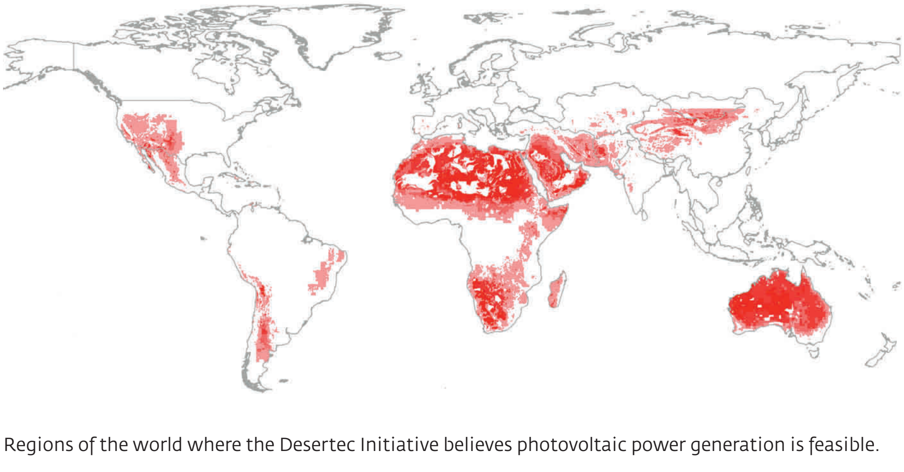
Even the work that these engines perform eventually converts into heat. When we drive by car from home to our vacation destination and back again, the chemical energy of the fuel consumed in the process has been converted into pure waste heat with the aid of the ever-present friction. This heat can't be used for technical purposes, and has drained away into the environment anyway.

THE EARTH SYSTEM CAN'T RUN BACKWARDS

In the 19th century, this realization from the world of nascent steam engines led to the theory of thermodynamics. What started with engineering became a field of physics that has fundamental significance for the earth system, as well. It is the laws of thermodynamics that give physical processes a direction.

"This is why the earth system can't simply run backwards like a film," explains Axel Kleidon, "that is, absorb cold, long-wave radiation from all directions in space and radiate hot, shortwave radiation to the sun as rays." This is something the visitor must first digest – especially since the scientist now steers toward a term with which even many physics students initially grapple: entropy.

Fortunately, we can all understand the nature of entropy with an illustrative example, as we battle it continuously in our everyday lives. Axel Kleidon's son is no exception. He likes to play with Legos, and every day he experiences something fundamental with which we are all familiar: The building



Regions of the world where the Desertec Initiative believes photovoltaic power generation is feasible.

Graphic: Bright Source Energy (top), Desertec Foundation, www.desertec.org

Photo: dpa – picture alliance

blocks, which are nicely arranged in boxes to start with, appear to spread themselves across the entire room. “This isn’t just a spatial effect, resulting in you eventually stepping on the bricks wherever you walk,” says Kleidon. “The orderly arrangement of the bricks according to their color also transforms into a colorful mix.”

In the child’s room, a mysterious force comes into play that – from the human point of view – strives to change nice order into not-so-nice disorder. This is nothing other than entropy, which increases as the apparent disorder increases. And it wants to carry on indefinitely.

Why is this so? This can be understood if one approaches the ever-present phenomenon from the viewpoint of statistical physics – the modern child of thermodynamics. In statistical terms, the tidy room where the Lego bricks are sorted into boxes according to color is only one state among an incredibly large number of equal states. Each of these states represents a different distribution of the Lego bricks across the room. This image makes clear that the tidy state is quite unlikely. If Kleidon’s son had tens of billions of years to play with Legos, this state would also occur at some time purely by chance – at least this is what the statistical consideration says. Since his son won’t live that long, he must actively tidy up. “And this spatial concentration and sorting requires work,” says Kleidon. This applies not only to Legos, but very generally.

SOLAR RADIATION IS ORDERLY, THE EARTH’S, DISORDERLY

Legos are therefore wonderfully suited to helping one understand the nature of entropy. The laws of thermodynamics state that entropy drives all natural systems toward maximum disorder. As always, it is also quite possible to resist the law. Life does so by utilizing energy to produce ordered structures: the photosynthetic reaction center in plant cells, for example, is a highly ordered molecular Lego set that collects sunlight in order to produce usable energy in the form of sugar.

But breaking the law, which ultimately doesn’t happen, has its price: somewhere else, entropy inevitably has to increase in order to compensate. Earth simply deposits this excess of entropy in space.

Axel Kleidon explains the export mechanism thus: “The radiation from the sun is highly ordered compared to the radiation from earth.” In fact, solar radiation is nicely ordered in two respects. On the one hand, all solar light quanta arrive with a clean spatial order from one direction – from the sun. The earth, however, re-radiates diffusely in all directions, so the spatial disorder is much greater. On the other hand, solar radiation consists of relatively few light quanta that harbor relatively large amounts of energy.

The cool re-radiation from earth into space, in contrast, contains many more light quanta that are relatively low in energy. In the Lego analogy, it might help to think of it like this: while the light quanta from the sun correspond to assembled Lego cars, the debris of individual bricks that results as play progresses corresponds to the radi-

On land, only around 5 terawatts of wind energy can be used sustainably. Wind parks in the ocean could increase this potential, not least because the low-level wind over the oceans carries around 375 terawatts, and over land only 125 terawatts, of which a mere fraction is available for energy generation.

ation from earth as the final state. Kleidon's conclusion: "The earth system increases the entropy of the radiation, and this provides its driving force."

ONLY A SMALL FRACTION OF THE WIND POWER IS USABLE

Solar radiation drives a hierarchy of many cycles on earth. It heats the earth's surface on land, for example, which in turn heats the layer of air above it like a hotplate. The warm air near the ground then rises like a hot-air balloon, taking moisture up to cloud level. Cold air then sinks to the ground, where it heats up. If this convection cycle runs during the day, it boosts the global wind and water cycle in the weather system.

The researchers in Jena can model these essential, major cycles in the earth system and realistically estimate how much of the solar power flows into each cycle. They can draw very concrete, astonishing conclusions from the results. This also applies to the question of how much power we can draw from the earth system in the form of renewable energy without changing it in the long term.

One example is the use of wind power over land. It is at the end of a chain that begins with 1,000 terawatts. This is how much power flows into the global production of wind as a result of solar heating. Around half of this is inherent to the wind near the earth's surface, meaning it can be reached by wind turbines. Since the land areas are smaller than the oceanic areas, 125 terawatts remain. However, turbulence in the atmosphere, or, simply, friction in the air, uses up another 77 terawatts of this. This leaves around 50 terawatts of wind power that can, in principle, be used for technical purposes over land.

If this power were used to the full, the global weather machine would begin to falter. A maximum of 10 percent could be sustainably used, estimates Axel Kleidon. These 5 terawatts thus correspond to just under a third of mankind's overall energy requirements.

Photo: iStockphoto

The good news, according to Kleidon, is that we can expand the use of wind power on land – and offshore – quite a lot in comparison to today. It is, however, subject to surprisingly narrow natural limits. The Jena-based researchers recently calculated that the fast jet streams of wind in the upper atmosphere could supply 200 times less energy – if it were already possible to use them – than was previously thought. This destroys many high-flying visions of floating wind parks in the stratosphere.

Solar energy, in contrast, is present in abundance. This affects the production of solar electricity, as well as food, which of course is converted solar energy. “There would therefore be no change in the overall balance if we were to simply convert existing farmland into solar parks,” explains the scientist. Instead, we must turn unproductive desert areas, which currently convert solar radiation unused into waste heat, into productive areas. So the Desertec Initiative, which is planning large-scale solar power stations in the Sahara, is basically heading in the right direction.

PHOTOSYNTHESIS PRODUCES 200 TW OF POWER WORLDWIDE

According to Kleidon’s findings, mankind can sustainably increase the overall power of the earth system if it uses solar energy intelligently. By doing so, it could actually manage the earth and herald a revolution similar to that ignited by the invention of farming.

Life itself has already been doing this for many millions of years – and that on a massive scale. The numbers in Kleidon’s power balance show this. In the global earth system, photosynthesis provides a gigantic capacity of more than 200 terawatts. That’s roughly four times as much as the contribution from geothermal power, and more than twelve times as much as our global consumption of primary energy.

Seen from space, this biotic productivity shows up not only in the green color of earth’s landscapes; as Kleidon points out, the relatively small-scale cloud formations, too, are ultimately a clear fingerprint of plant activity on earth. Rainforests, such as the Amazon, have a massive impact on the local weather and thus the cloud structures in a very localized area – which, on a global scale, is what even the Amazon represents.

WITH DEEP ROOTS, PLANTS COOL THE CLIMATE MORE STRONGLY

In fact, it was the vegetation of the Amazon that brought Kleidon to his research field. “In the southern hemisphere, there is a marked dry season in the tropics,” he explains. However, in the Amazon basin, it never gets as hot as the climate models from Kleidon’s time as a doctoral student erroneously calculated. A report in the journal NATURE on the deep roots of the rainforest trees in the Amazon gave Kleidon an idea about where the error might lie. He designed a “grounded” climate model that took the root systems of the trees into account.

During the dry season, deep roots allow plants to draw more of the excess water that is stored in the soil from the rainy season. The trees can thus vaporize a lot of water even in the dry season. And in fact, the new model then simulated a much cooler climate that comes close to reality in the Amazon. “The effect was enormous,” says Kleidon, whose delight is still evident today.

The result of this plant activity is that real mushroom clouds – for example thunderstorm cells – are produced above such rainforests. Such sharply defined cloud structures are lacking on Venus and Mars. So for extraterrestrial astronomers, there are countless signs that would indicate that there is vibrant life on planet earth. ◂

TO THE POINT

- **On earth, different forms of energy are continuously being converted from one form to another. During this process, our planet emits as much energy in the form of radiation as it absorbs.**
- **The entropy of the radiation emitted is significantly greater than that of the radiation that is absorbed, because the earth radiates heat in all directions and emits many more light quanta than it absorbs; in exchange, the energy of the individual light quanta is much lower.**
- **Only around 5 terawatts from the wind on land can be used without serious side effects – this corresponds to one-tenth of the available wind energy, and just under one-third of mankind’s current primary energy requirements.**
- **Solar energy can supply mankind’s energy requirements; but it makes sense to build solar power plants in deserts, where no plants are already using the solar energy.**

GLOSSARY

Entropy: This is derived from the number of states a system can take on and still have the same energy content. Since there are always many more equally energetic disordered states than ordered ones, the entropy of disordered systems is greater than that of ordered ones. Entropy is thus often illustrated as the measure of disorder. Processes occur spontaneously only if the entropy of the entire system increases in the process. Finally, entropy is also deemed to be a measure of the quality of energy. If energy has a high quality, it means that work can be done with it.

Earth system: In this concept, the earth is seen as a system in which the atmosphere, rivers and lakes, ice, soil and rock, and life interact with each other in a multitude of ways.

Photosynthesis: This process converts light energy into chemical energy. Plants, bacteria and algae use it to produce, among other things, sugar from carbon dioxide and water, releasing oxygen in the process.

Thermodynamics: Describes the rules for possible energy conversions. It can be used to determine, for example, how much work a system can perform when energy is converted from one form into another.