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- THEME: GREEN PRECISION
- MANUFACTURING TECHNIQUES FOR CO_2-CAPTURING MATERIALS PRODUCTION
- NEXT LEVEL IN LASER GUIDE STAR CREATION
- PRECISION FAIR 2022 REPORT – GROWING HIGH-TECH AMBITIONS

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The cover illustration (source: Shutterstock) depicts the contribution (precision) engineering can make to solving the energy and climate-change challenges. See the articles on the pages 5 ff, 8 ff, and 14 ff.

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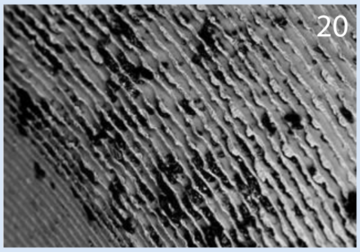

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FEATURES

CLIMATE CHANGE SELLS HORRIBLY!

We all know it: we need to fly less, take the bike more often, eat less meat and turn down the thermostat in our homes... We know we should do it, but most of us take only tiny steps in the right direction, if any at all. Why is it so difficult to change for the sake of our planet?

Climate change sells horribly: if you do everything 'wrong', there are no direct consequences for you personally and if you do everything 'right', there is no direct reward either, only your own morals that might be slightly satisfied. Every political party knows that we need to act, but if they include tax increases for the 'finer things in life' into their political agenda, they will lose many votes.

Earlier this year, I attended a congress on the energy transition at the PSV stadium in Eindhoven (NL). Heleen de Coninck, Professor of Socio-Technical Innovation and Climate Change at Eindhoven University of Technology, had the opening statement and her conclusion was clear: the window is rapidly closing, but we might still pull it off if we achieve a series of daunting targets on time. The energy in the room was tangible; the challenge is huge, but we'll step up!

The next presentation was about a centralised heat pump project in a district in Den Bosch (NL). Technically very promising. The questions from the audience at the end, however, revealed a couple of weaknesses: despite a return-on-investment of just a few years, only about 20% of all households could afford to participate, the project would take 12 years to complete (far exceeding all deadlines that De Coninck had mentioned), and moreover, the project might not continue at all because the district is a protected city view...

Are we really going to allow such a great initiative to fail due to reasons like that?! I don't know about the rest of the audience, but I personally felt a bit defeated. Are we going to stand around in a circle, pointing to each other that they are the reason we cannot move forward?

Of course not! We are engineers and we solve problems. The number of technical solutions being developed for the energy transition is insane and seems to increase by the day. Electric vehicles, PV and heat pumps in more and more homes, development of energy-storage solutions (both electrical and thermal, both for home use and on industrial scale), green hydrogen and synthetic fuels. As ETS (Emissions Trading System) exemptions are coming to an end, we are also seeing the big players like Tata steel coming in motion.

So, I think mankind will be able to come up with excellent new technologies to face the massive challenge of climate change. If you ask me, it will not depend on technology whether or not we will succeed at turning things around on time, but on policy and changing the behaviour of all of us.

The world needs a global PR campaign to 'sell' climate change. Make it attractive to do the 'right thing'. Not just because the gas bill is so high, but because it matters and because it cannot wait!

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BYE BYE PRIMARY BATTERIES, HELLO ENERGY HARVESTERS

Harvesting vibration energy from the environment and storing it in a capacitor or a rechargeable battery provides a solution for powering devices such as sensors in an Internet-of-Things network. Kinergizer develops state-of-the-art motion energy harvesting solutions that ensure uninterrupted operation of these low-power devices, making primary batteries unnecessary. Predictive maintenance is one of the promising applications.

ERIK VAN DE WETERING

Introduction

Over the last couple of years, large steps have been taken in implementing sustainable and green alternatives for energy production. Think of renewable energy solutions such as wind turbines, solar farms, hydropower plants and tidal energy. These technologies are all examples of energy harvesting: extracting a part of the ambient energy and converting it into electrical energy. For instance, in a hydropower plant, part of the kinetic energy of the water is converted into useful electrical energy, while a photovoltaic panel converts a part of the radiant energy of the incident light.

The previous examples are all on the megawatt scale. On the milliwatt scale, however, innovations for green energy can be made as well. These are based on another type of ambient energy that has a lot of undiscovered potential: vibration energy harvesting. Although vibration energy harvesting does not have the same impact in terms of generated electrical power as the examples mentioned above, it can play an instrumental role in the development of key Internet-of-Things (IoT) applications, which will impact everyone on a daily basis.

For example, by implementing vibration energy harvesters, the lifetime of wireless sensor networks in vibration-heavy environments can be greatly extended by eliminating the need of early replacement of their batteries. This saves costs and makes wireless sensor networks a more sustainable solution. But how can a vibration energy harvester enable such a benefit?

AUTHOR'S NOTE

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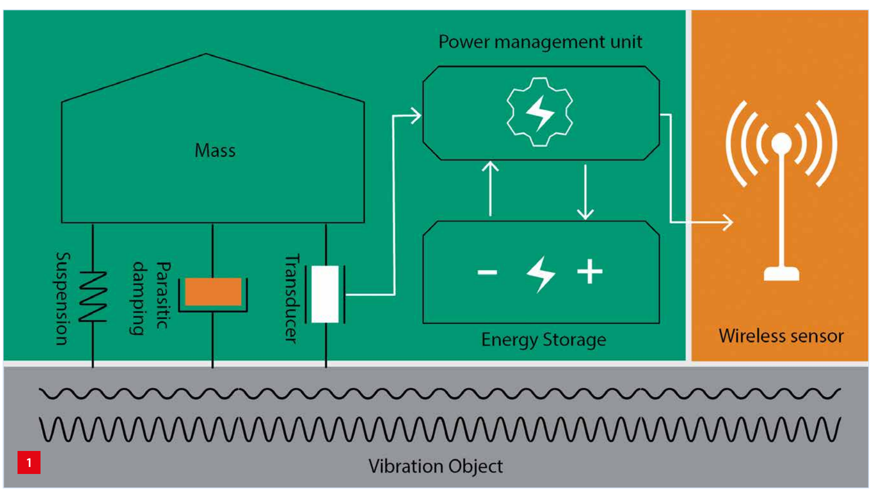

1 *Schematic representation of a vibration energy harvester unit.*

Basic working principle

With vibration energy harvesters, a part of the energy present in ambient vibrations is scavenged and transduced into electrical energy. Figure 1 shows the basic working principle of a vibration energy harvester (for confidentiality reasons, no more details can be shared). A vibrating object to which the harvester has been mounted transfers energy to the energy harvester. A mass suspended in the harvester then starts to build up kinetic energy. Part of the energy of the mass is inevitably dissipated into some parasitic damping, which is always present. Another part of the kinetic energy is intentionally extracted from the mass by a transducer. This component transduces the mechanical kinetic energy into electrical energy. The power management unit then makes sure that the energy storage, which can be a supercapacitor or a rechargeable battery, can be charged and that a sensor unit can draw power from it.

Predictive maintenance

An interesting use case for energy harvesting devices is predictive maintenance. No machine will last forever. At a certain point, parts have reached their end of life and failure

Application example of Kinergizer's energy-harvesting solution.
(a) The Hiper-D energy harvester (ø35 mm, 75 mm height, 90 g mass, 1-5 mW power).
(b) Mounted to a train bogie axle box.

of the machine will occur. Of course, nowadays the lifetime of components can be accurately predicted, but a premature failure of components does still happen. The consequences of such failure can be severe and, in some cases, can even endanger lives.

Mitigation of machine failure is therefore of great importance. Several known methods exist, the oldest of which being reactive maintenance: when a part fails, it is replaced. Of course, this does not prevent machine failure and is therefore not very effective. A better version is preventive maintenance. Parts are checked periodically and replaced based on a schedule. Using this maintenance scheme, parts could be replaced too early, increasing waste and costs. Next to that, periodical checks rapidly become expensive due to the involved man hours and potential machine downtime.

This has led to the principle of predictive maintenance: using wireless sensor nodes to track changes in e.g. temperature and vibrations, the health of a machine can be monitored. An accurate prediction of the required service interval can then be made, saving costs and minimising downtime. Advanced sensors do not only determine that a failure is imminent, but can also pinpoint the component that is close to failure.

The sensors used are mainly powered by primary batteries and just like machines, primary batteries do not last forever. Depending on the capacity of the battery, the number of variables to process and the measurement interval, the power consumption of the sensor node can quickly become too large. The batteries are then likely to be depleted before the service life of the component that the sensor is meant to monitor. As a result, the battery must be replaced to continue the monitoring and this is often a costly process. It is important to note that, although batteries might not be expensive, replacing them actually is. The batteries are often placed together with the sensor in a sealed package, making it infeasible to replace the battery only; the entire unit must be replaced. The sensor nodes are also often located at places that are hard to reach, which leads to more downtime of the equipment and more required labour for replacement. Therefore, although batteries are not expensive, the additional factors escalate the operational costs quite rapidly. Taking all this into consideration, predictive maintenance fails to serve its purpose in this way.

Fortunately, this is a problem that can be solved. As vibrations and reduced service life of components often go hand in hand, vibration energy harvesting forms a perfect solution to this issue, by utilising an energy harvester and a rechargeable battery to power the sensor. A good example where this principle can be applied is the railway sector.

Railway sector

Railway transport is deemed to be one of the greenest ways of transport and is on its way to achieving net-zero carbon emission. To make travelling by train appealing to the traveller, train arrival times must be accurate and precise, so the system needs to be reliable with minimum downtime. The high reliability of the train bogies (chassis) plays an important part in achieving that goal.

Currently, wireless sensor nodes powered by primary batteries are already being used to monitor the health of the bogie. However, the lifetime of those batteries is a limiting factor to the sensor. Either the power consumption of the sensor must be budgeted, limiting its capabilities, or the sensor's lifetime is only limited to a few years, increasing the operating costs by an imminent need for early sensor replacement.

Kinergizer aims to provide an energy harvester solution that increases the power budget of the mounted sensor while ensuring that the sensor can operate reliably for at least ten years or more. Figure 2 shows an energy harvester mounted to a train bogie axle box.

Train bogies are subject to a harsh vibration environment with large vibration amplitudes. Depending on the speed and other conditions of the train, large variations in amplitude and frequency content can be expected. To guarantee a reliable output power, the energy harvester must not be too dependent on a specific input vibration: it needs to be robust to varying input conditions.

Kinergizer's energy harvester solutions are therefore engineered in such a way that they supply a sufficient amount of power to the sensor for all foreseeable vibration conditions. Figure 3 illustrates this concept: whether the signal's frequency or amplitude is low or high, or whether the signal is wideband, ideally the energy harvester can scavenge a sufficient amount of energy in all cases.

TOWARDS NEGATIVE EMISSIONS THROUGH DIRECT AIR CAPTURE

Every day, the news has some mention of climate change. A flood, a forest fire, a climate summit, climate protestors,... Climate change is real and it is happening faster and faster. The world needs solutions with a real impact to tackle climate change. Carbyon is an Eindhoven-based start-up company, developing novel equipment to help solve the biggest challenge humanity has ever faced. To make use of Carbyon's USPs, advanced manufacturing techniques are needed for the production of CO_2-capturing materials. Carbyon is developing their own dedicated set-up for this, which will be explained in detail.

JASPER SIMONS

Carbyon's mission

Carbyon's founder and CEO Hans de Neve was working on novel thin-film materials for solar applications at Solliance. The idea arose to apply these materials for capturing CO_2 directly from the atmosphere (direct air capture, DAC). Some 'Friday-afternoon' experiments were done and results looked great. The principles were patented by TNO shortly after. Because TNO did not want to pursue DAC at the time, De Neve decided to spin out and found his own company, fortunately supported fully by TNO. Carbyon joined the programme of Eindhoven-based venture builder HighTechXL and made great progress in acquiring essential testing equipment and proving the fundaments of the technology in lab-based experiments (technology readiness level TRL 4).

Early 2021, Elon Musk tweeted, "Am donating $100M towards a prize for best carbon capture technology", and engaged in a cooperation with X-prize, an independent international organisation with the goal to accelerate innovation through competition. With Musk's $100M as the biggest prize-pot in X-prize's history, the 4-year contest started in April 2021. The challenge is to present a carbon-capture solution that can be scaled to gigaton scale. As this contest fits Carbyon perfectly, we joined right away.

The competition consists of two parts; after the first year (in April 2022) it was possible (not obligated) to participate in the 'Milestone Award' and the big final will take place in April 2025. The Milestone Award consisted of a sizeable submission on paper, comprising a description, calculations and hard evidence from lab measurements. On Earth Day 2022, we received the news that we had won one of the 15 $1M prizes from the hundreds of submissions worldwide. To be able to compete in the final, the challenge is to capture and store 1,000 tons of CO_2 within the timespan between 1 February 2024 and 1 February 2025.

Today, the team has grown to about 20 people in house and dozens more in external cooperations with companies and academics in the region. The mission of Carbyon is to slow down, stop and eventually reverse climate change by restoring the carbon balance in the atmosphere.

AUTHOR'S NOTE

Jasper Simons studied Mechanical Engineering at Eindhoven University of Technology (TU/e) and graduated from the Constructions and Mechanisms group. He worked at CCM (now Sioux) and MI-Partners, in the field of high-tech mechatronics, and in 2020 became the CTO of Carbyon in Eindhoven (NL).

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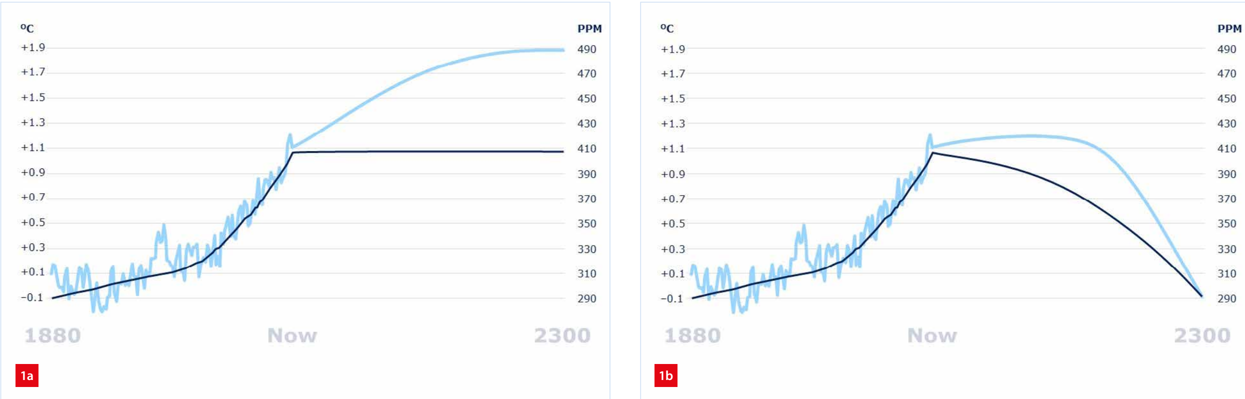
Climate change

Luckily, by now, most people understand that climate change is real, that it is moving faster than ever, that it is caused by human behaviour and that it has devasting effects on our own environment. The CO_2 in our atmosphere allows energy from the sun to reach the earth's surface, but keeps the energy within the atmosphere. The higher the CO_2 concentration in the atmosphere becomes, the more energy is 'kept' in our atmosphere.



To stop global warming (blue) due to rising CO_2 concentrations in the atmosphere (black), CO_2 emissions have to decrease.
(a) With net-zero emissions, temperature will still rise.
(b) Negative emissions are required to bring back the global temperature to an acceptable level.

The vast amount of thermal mass in the earth's surface and atmosphere causes the response of our 'system' to be rather slow. As a result, the temperature on earth is presently not in equilibrium with the CO_2 concentration in the atmosphere. This means the following: Even if we would stop emitting CO_2 tomorrow completely, reaching true net-zero emissions worldwide, even then climate change will not stop. Because we are not at equilibrium yet, the IPCC (Intergovernmental Panel on Climate Change) concludes that climate change would continue for another three hundred years before levelling off. It is this realisation that stresses the need for negative emissions (Figure 1). This requires the removal of all the CO_2 we emitted over the past 150-200 years, cleaning up our own mess. And then, hopefully, climate change would indeed slow down, stop and even reverse...

Carbon balance

All the CO_2 we emit, comes from carbon that was already on earth in a different form. Strongly simplified, carbon occurs on earth in three 'forms':

- Biosphere: in plants and trees, in the oceans, in animals and also in our own bodies.
- Atmosphere: CO_2 gas.
- Underground: mineralised in rocks and sediments, but for the sake of this story, predominantly in the form of fossil fuels.

Many processes occur naturally that exchange carbon between these different forms. Starting from the industrial revolution, humanity started burning vast amounts of fossil fuels, taking large quantities of carbon from underground and emitting it into the atmosphere. In doing so, we strongly unbalanced the naturally occurring carbon cycles. We need to undo this by removing the CO_2 from the atmosphere again and this is exactly what Carbyon's equipment is being designed for.

What to do with all that CO_2?

The captured CO_2 can go in two directions: Carbon Capture and Utilization (CCU), and Carbon Capture and Sequestration (CCS)

CCU

There are many industries that use CO_2 as a feedstock. Examples are the chemical industry, merchant gas suppliers (such as Air Liquide or Linde gas), greenhouses (will be addressed later) and the beverage industry (e.g. Coca-Cola). An additional market that is presently still small but is expected to grow to huge proportions is the synthetic fuel market, which uses CO_2 and green hydrogen to synthesise fuels such as kerosine.

The CO_2 these markets use, often comes from fossil sources and ends up in the atmosphere sooner or later. The shortest imaginable cycle is the beverage industry. They put CO_2 in their products and after a shelf life of a couple of weeks, a consumer will drink it, burp and the CO_2 goes into the atmosphere. The same happens in greenhouses. They use CO_2 to help crops such as tomatoes grow. After a few weeks of growing, consumers eat them, burn the fuel they supply and exhale the CO_2 into the atmosphere.

In each of these industries, fossil CO_2 sources could be replaced by CO_2 captured from air. As mentioned, all of these industries have in common that the CO_2 will eventually end up back in the atmosphere, which is where it came from with DAC, making this a CO_2-neutral cycle.

CCS

Contrary to utilization (CCU), sequestration (or storage; CCS) means that CO_2 is taken out of the cycle permanently (or at least for several centuries). There are two major 'sinks' for CO_2: ironically (or beautifully) underground, or locked in building materials such as concrete. Underground storage can be done in depleted natural gas fields. There are not many sites operational yet, but scientists agree that this is a safe and sustainable way of storage and the available capacity is huge.

Alternatively, CO_2 can be mineralized in certain rock formations, such as olivine and basalt. For example, the captured CO_2 can be dissolved in water and pumped into underground porous basalt layers where the CO_2 mineralises and stays there forever. This mineralisation can also be done above ground (sometimes called enhanced weathering). The resulting minerals can be used as a replacement for cement, storing the CO_2 inside concrete from which it will also never be released, not even if the concrete is later demolished. This solution really cuts both ways as it reduces cement production, which is a huge emitter of CO_2, and it sequesters CO_2 from the atmosphere.

Summary

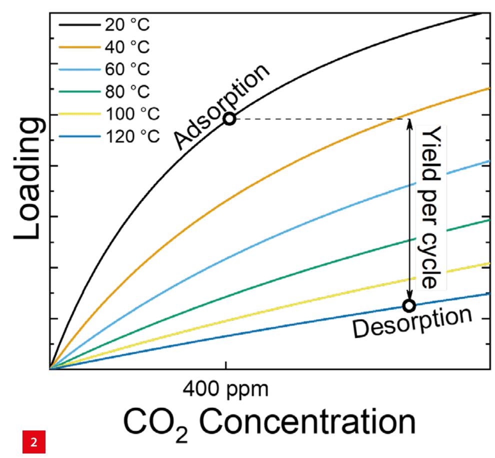
Although CCU applications are 'only' net zero, they actually support Carbyon's mission. To get to net negative emissions worldwide, we first need to get to net zero. This means reducing the use of all fossil fuels as quickly as possible and replacing the old-fashioned processes with renewable processes based on CO_2 from air. On top of that, we need to ramp up as much CCS as we can. The negative emissions we create there will first serve to compensate hard-to-abate CO_2 emissions (such as commercial aviation, which cannot easily be electrified). As emissions are reduced and CCS is scaled up, actual net negative emissions will be achieved as well.

Direct Air Capture

Recently, the concentration of CO_2 in the atmosphere has exceeded 420 ppm, which is 150% of the 280 ppm before the industrial revolution, but even then, 99.958% of the atmosphere is not CO_2... Removing CO_2 from the atmosphere is therefore like finding a needle in a haystack over and over again; only one in every 2,500 molecules is CO_2. Hence, we need a way to specifically target the CO_2 and let everything else pass. This is achieved by a thermal- and pressure-swing chemisorption process.

There are two main groups of chemicals that can capture CO_2 molecules by forming a covalent bond; amines and carbonates. These chemicals cannot be used as stand-alone materials, so they have to be coated onto a carrier structure. The combination of the carrier structure and the active chemicals is called the sorbent, which is exposed to the air at ambient pressure and temperature. CO_2 molecules will hit the surface and some of them will stick to it (forming the aforementioned covalent bond). This is called adsorption and it is an exothermic reaction, which results in a relatively stable bond.

Adsorption and desorption are continuously taking place side-by-side. The net amount of CO_2 on the sorbent is influenced by temperature and partial CO_2 pressure. Higher temperature results in more desorption, so less CO_2 on the sorbent, and vice versa, and higher partial pressure of CO_2 results in more adsorption, so more CO_2 on the sorbent and vice versa. The influence of temperature is stronger in our case. The relation between CO_2 loading on the sorbent, temperature and partial CO_2 pressure is described by isotherms (Figure 2).



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Isotherms showing the relation between CO_2 loading on the sorbent, temperature and partial CO_2 pressure.

After a certain adsorption time, the sorbent reaches sufficient loading to be desorbed. Because the sorbent is heated, the equilibrium shifts towards desorption and the CO_2 is released again. As mentioned, adsorption takes place under atmospheric conditions, but obviously, desorption cannot. The CO_2 would be released back into the atmosphere then, making the entire process useless. Ad- and desorption phases therefore have to be separated in place (spatial) or in time (temporal). Carbyon has chosen the latter, which results in a batch process where ad- and desorption are separate steps, carried out sequentially. The resulting machine and process layout is presented in Table 1. Upon completion of the desorption step, the vessel is vented to atmospheric pressure again and the cycle can start over.

Carbyon's USP

Carbyon is not the only entity pursuing DAC and most of our fellow climate-change-fighters use very similar processes: temperature (and pressure) swing of amines or carbonates. Carbyon's USP is speed. For any DAC process, one of the biggest challenges is mass transport; how do the CO_2 molecules from the bulk airflow find their way to a 'binding site' on the sorbent?

The biggest difference here is illustrated in Figure 3, showing a generic cross-section of a carrier material, which is porous to enlarge the surface area and available volume for the sorbent. The left image shows how most competitors coat their carriers; the pores are completely filled up with sorbent. This results in a high mass percentage of the active chemicals, which is good for the capturing capacity. But all gas-to-solid interactions can only take place on the surface area of the coated carrier structure, resulting in rapid saturation of the outer layer. To reach the deeper binding sites, the already adsorbed CO_2 molecules have to 'move over' to free up binding sites on the surface again. This 'moving over'