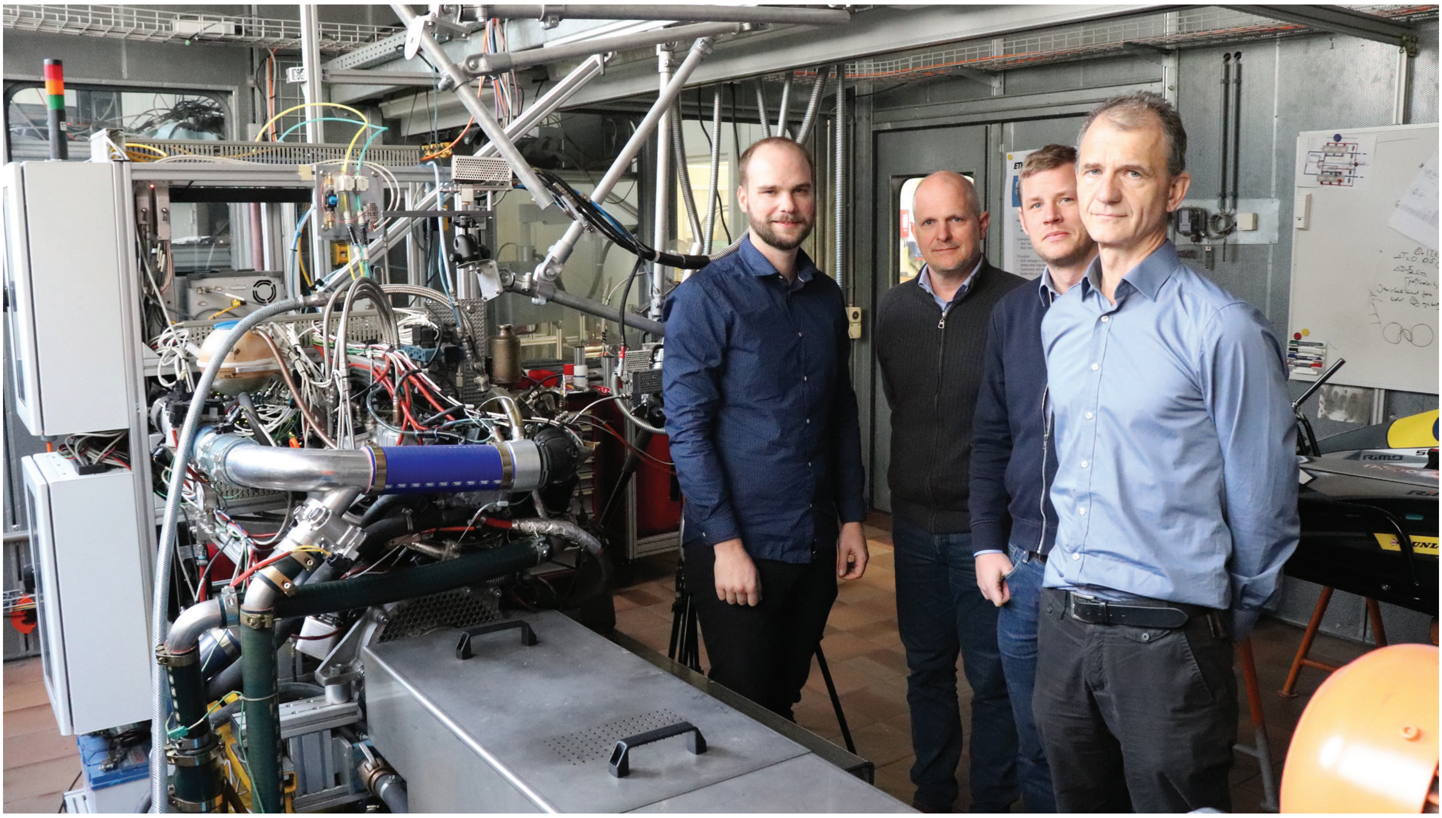
AN ENGINE MADE FOR RENEWABLE FUELS

Electromobility has inspired great hope. Efficient combustion engines that are as environmentally friendly as possible can also contribute to sustainable mobility. This applies not only to the transport sector but also to air and sea transport, where electric mobility can today only be implemented in niche applications. Against this backdrop, three teams of researchers from ETH Zurich and Empa have joined forces in an interdisciplinary project to investigate how internal combustion engines can be made fit to use of renewable, CO_2-neutral fuels from biogenic sources ('biofuels') or produced synthetically with renewable electricity ('e-fuels'). Important results will be put into action in cooperation with industrial partners.



Project team in front of the NextICE engine test bench at ETH Zurich (from left to right): Richard Hutter (ETH Zurich/IDSC), Dr. Patrik Soltic (Empa Vehicle Drive Systems Department headed by Christian Bach), Dr. Christophe Barro (LAV, ETH Zurich headed by Prof. Konstantinos Boulouchos), Prof. Christopher Onder (Head of the Institute for Dynamic Systems and Control /IDSC at ETH Zurich). Photo: B. Vogel

A technical report about the results of a research project in the field of mobility, which was financially supported by the Swiss Federal Office of Energy. The report has been published in the technical magazine Swiss Engineering STZ (issue May 2019).

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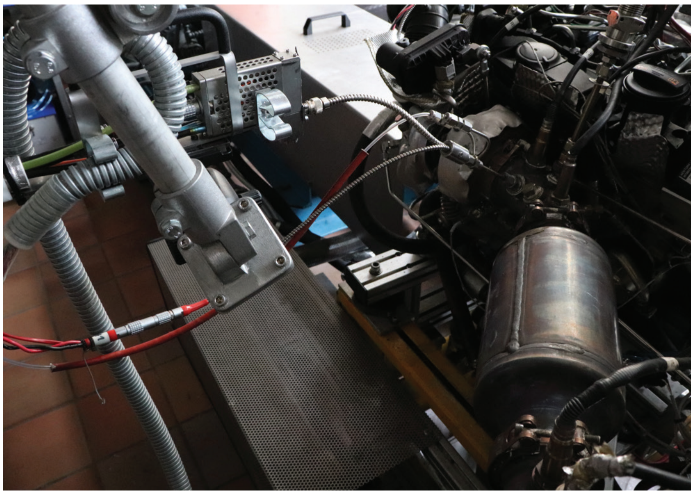
With a market share of 1.6%, biofuels are a niche product in Switzerland. Renewable fuels in the form of biodiesel (primarily in the form of a 7% admixture with diesel) and bioethanol (primarily available as a 5% admixture with petrol) are used. In addition, gas-powered cars run on biomethane, and some farmers fill their tractors with vegetable oil, especially rapeseed oil. The biofuels used in Switzerland come mainly from animal or vegetable waste and residues. Countries such as the USA and Brazil, on the other hand, cultivate energy crops on a large scale. "Rapeseed diesel," which is widespread in Europe, is also produced from the rapeseed plant (with the addition of methanol).

Because of competition from food production, critics strictly reject biofuels. Proponents, on the other hand, see biofuels as an important approach to replacing fossil fuels and as a step towards CO_2-neutral mobility. Proponents claim that biofuels can also be produced without the use of food plants. This is the case, for example, when sewage sludge or agricultural waste is fermented into biogas and then refined into biomethane. Or if a synthetic fuel such as OME is used (see text box), which can be produced from CO_2, water and renewable electricity, for example, or regeneratively produced methane. With such fuels, proponents hope, the vision of a CO_2-neutral combustion engine could become reality.



Close-up of the NextICE engine test bench at ETH Zurich: The cables lead to a measuring probe with which unburned methane is measured. The pollutants are removed in the three-way catalytic converter on the right. Photo: B. Vogel

Loose Cooperation

Against this background, scientists from ETH Zurich and the Swiss Federal Laboratories for Materials Testing and Research Empa in Dübendorf (ZH) carried out the NextICE project from 2014 to 2018. The focus was on the question of what a future internal combustion engine (ICE) should look like that is designed to operate on renewable fuels. "Combustion engines have so far been optimized for fossil fuels such as gasoline and diesel. If we want to operate them with renewable fuels in the future, we have to redesign the combustion engine - this applies not only to the combustion processes and control techniques used, but also to the mechanical design of the engine," says Prof. Christopher Onder, ETH Professor and head of the NextICE project.

Onder then highlights the three central questions that were worked on by each research team within the framework of the project: The ETH Laboratory for Aerothermochemistry and

A FUEL CALLED OME

OME (Polyoximethyldimethylether) is under discussion as a clean (i.e. CO_2-neutral) replacement for diesel fuel. In order to meet this demand, OME must be produced without fossil resources and using renewable electricity (e.g. synthesis gas from CO_2 and water using renewable energies; or from renewable raw materials).

OME is not highly volatile and highly flammable like diesel, but contains oxygen. This is both an advantage and a disadvantage: One advantage is that the oxygen contained in the fuel practically prevents the formation of soot and thus allows operation without excess oxygen (stoichiometric as with gasoline, in contrast to lean combustion with diesel). This in turn enables the use of a compact 3-way catalytic converter. Another advantage: OME is liquid and could therefore be easily distributed over the existing filling station infrastructure in the future. The disadvantage: Because of its oxygen content, OME has a lower energy density and therefore requires a larger tank for the same driving performance.

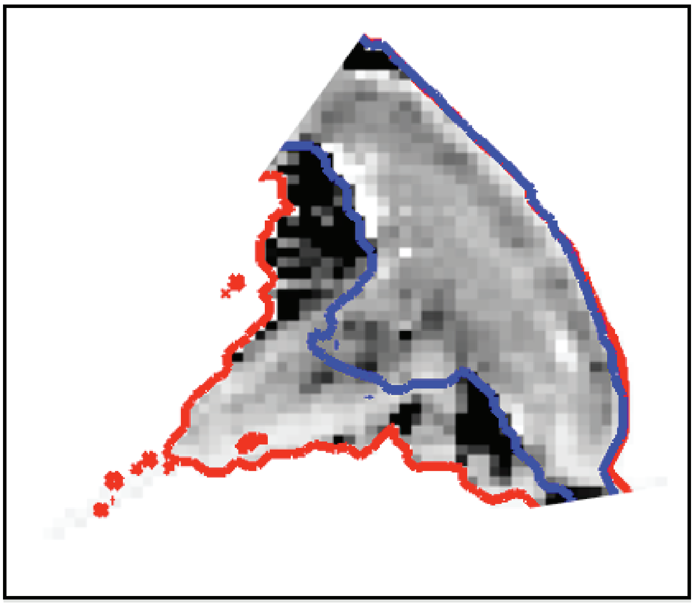
OME can be used alone as fuel in a diesel engine - or mixed with diesel in small quantities. Third possibility: OME is used in a pilot injection engine in which methane (natural gas) is ignited by the diesel-like OME. BV

Combustion Systems (LAV/Prof. Konstantinos Boulouchos) was dedicated to the new combustion processes; the ETH Institute for Dynamic Systems and Control (IDSC/Prof. Christopher Onder) to control technology, while the Empa Vehicle Propulsion Systems Department (Christian Bach) was responsible for engine design issues. In each of the three subprojects, the three partners worked on their own questions, but communicated and interacted to establish important links. "This relaxed cooperation was very helpful and has brought us forward," says Christopher Onder.

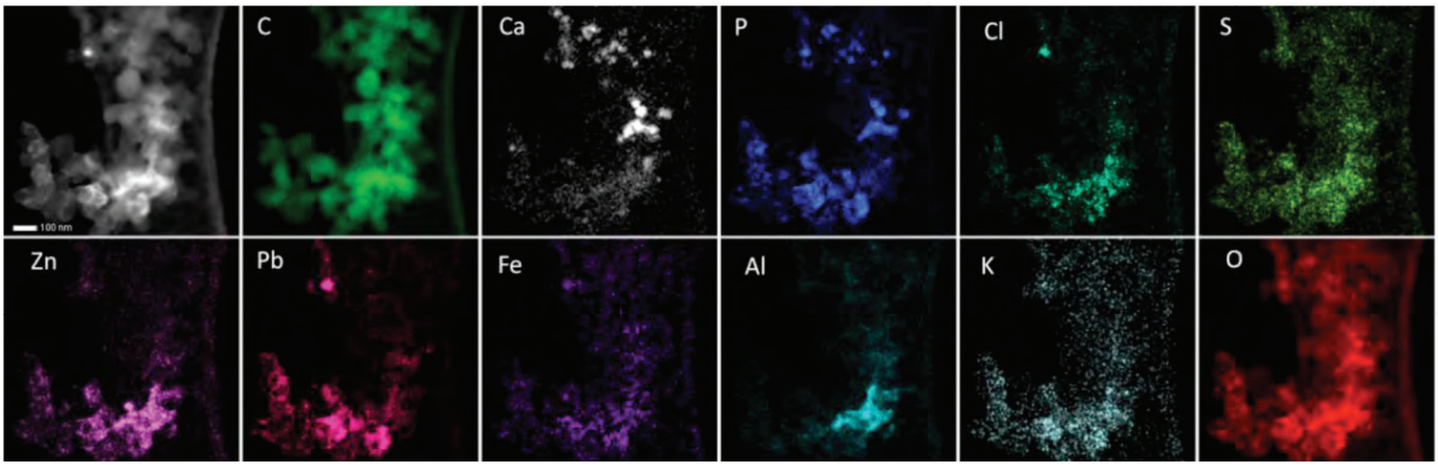
OME Motor Enables Compact Catalytic Converter

In their subproject, the LAV researchers studied the combustion of OME fuel in an insulated combustion chamber and a special single-cylinder experimental diesel engine. For their study, they used pure OME as fuel as well as OME mixed with diesel fuel. A key result: the combustion of pure OME produces practically no soot. The big advantage is that exhaust aftertreatment can be greatly simplified when using OME compared to diesel: under current legislation, a fine particulate filter can be dispensed with, as can an SCR system for reducing nitrogen oxides. These, together with CO and unburned hydrocarbons, can then be removed in a compact 3-way catalytic converter.

This advantage convinced the Swiss construction machinery manufacturer Liebherr (Bulle/FR) to join forces with ETH researchers in a follow-up project: The project, which was already



During the combustion of OME, the oxygen contained in the fuel prevents the formation of soot. The image - 1.4 milliseconds (ms) after the start of injection (SOI) - shows the soot contour of a fuel stream (injection from bottom left to top right) as the difference between two experimental set-ups: In the first experiment (outer contour in red) 5% OME was added to diesel, in the second experiment (outer contour in blue) 50%. In the second case less soot (dark surface) is visible. If the test is carried out with pure OME, no soot is visible at all. The soot was made visible using 2-color pyrometry. Graphic: Iannuzzi, S.E., Barro, C., Boulouchos, K., and Burger, J., "Combustion behavior and soot formation/oxidation of oxygenated fuels in a cylindrical constant volume chamber." Fuel, 2016. 167(Supplement C): p. 49-59, doi: https://doi.org/10.1016/j.fuel.2015.11.060.)

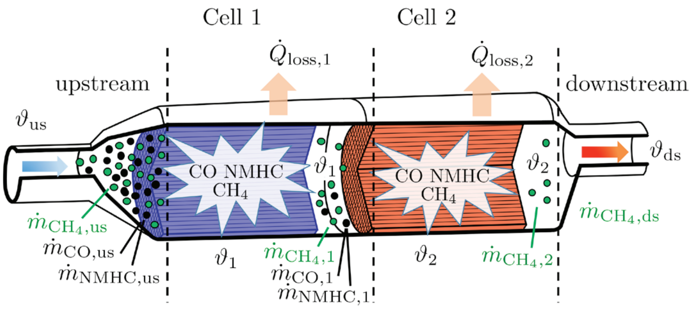


Transmission electron microscopy shows the presence of twelve chemical elements on a soot particle in the exhaust gas of the 1-cylinder research engine after the combustion of pure OME. Interestingly, the detected elements do not originate from the fuel, but from the lubricating oil. The researchers at the ETH Laboratory for Aerothermochemistry and Combustion Systems (LAV) were able to demonstrate this by examining the composition of the particles. Graphic: Barro, C., Parravicini, M., Boulouchos, K., and Liati, A., "Neat polyoxymethylene dimethyl ether in a diesel engine; part 2: Exhaust emission analysis." Fuel, 2018. 234: p. 1414-1421, doi: https://doi.org/10.1016/j.fuel.2018.07.108.)

supported by the Swiss Federal Office of Energy (SFOE) as NextICE, is to develop an engine based on OME fuel with a compact catalytic converter for construction machinery. These construction machines could be operated with a CO_2-neutral fuel. The downside, however, is that the fuel has a lower calorific value than diesel and also costs more.

Optimum Methane Engine Operation

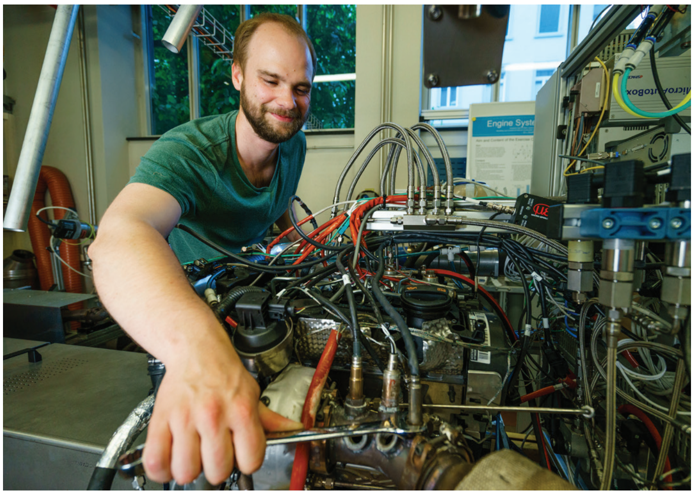
The scientists around Prof. Onder approached the problem of a new combustion engine from the control engineering side. Among other things, they wanted to know what the optimal operating strategy is for an engine powered by biofuels or sustainable synthetic fuels. The operation of a passenger car is very dynamic and the engine must therefore be able to change speed and torque quickly. "An engine works at different operating points and has to master the transitions between them well; this is a great challenge, especially for fuels that are similar to petrol and therefore difficult to ignite, such



Mathematical models play an important role in engine research at ETH Zurich. The illustrated scheme of a modified diesel catalyst (oxidation catalyst) is used to create a mathematical model of the chemical processes that take place in a catalyst. ETH researchers are particularly interested in the harmful exhaust gases carbon monoxide (CO) and unburned hydrocarbons (including methane/CH_4 and non-methane/NMHC). Using the mathematical models, scientists can determine, among other things, the temperature at which the harmful exhaust gases are most effectively burnt in the catalytic converter. Illustration: IDSC

as methane, ethanol and methanol," says Richard Hutter, the main researcher in Prof. Onder's research group. Hutter has written his doctoral thesis as part of this project.

Richard Hutter focused his investigation on methane. Methane is the main component of natural gas, but can also be produced from biogenic sources - such as biogas - or synthetically using renewable electricity. Methane is already used today as a fuel in cars powered by a gasoline engine that has been converted to run on natural gas. Richard Hutter went one



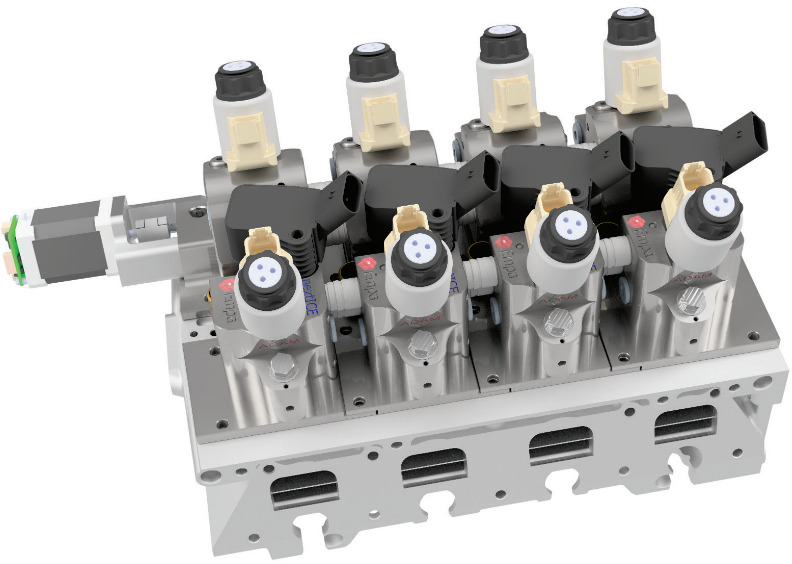
As part of his doctoral thesis at ETH Zurich, Richard Hutter carried out experiments on a modified diesel engine (dual fuel engine): In the engine, self-igniting diesel is used to ignite difficult to ignite methane. Photo: IDSC

step further in his study: he used methane in a modified diesel engine: In the so-called dual fuel engine, the self-igniting diesel is used to ignite the difficult to ignite methane. In his study, the ETH researcher was able to demonstrate a decisive advantage of this concept: "With the dual fuel-engine, we were able to increase the efficiency of the methane-powered engine by 5 percentage points to 42%, i.e. we achieved the efficiency of a diesel engine with methane, a fuel that is similar to gasoline," Hutter summarizes one of the main results of his study.

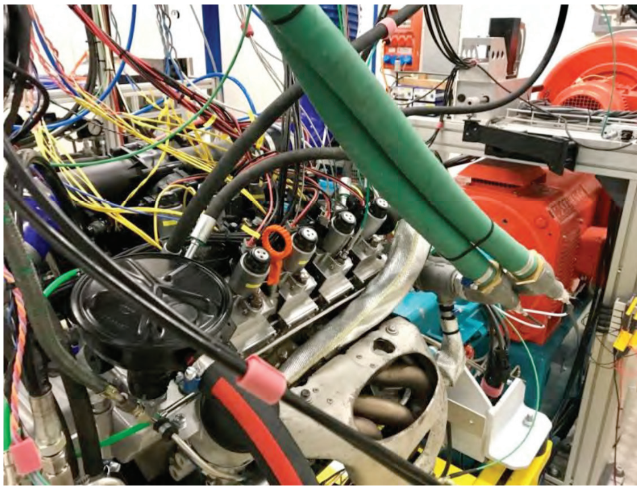
The researchers focused their attention on efficient and cost-effective exhaust aftertreatment, which places high demands on the highly efficient methane engine. Hutter's study uses mathematical models to describe the conditions under which a dual fuel engine can be operated within the legal emission limits. This is possible if the exhaust gas temperature is selected in such a way that the unburned methane in the exhaust gas oxidizes as completely as possible, thus minimizing the emission of this particularly problematic greenhouse gas. The results are currently being incorporated into a follow-up European project involving the VW Group.

Farewell to the Camshaft

While the NextICE studies presented so far were based on the combustion process or the operating control system, Empa researchers in the third subproject were working on reinventing the gasoline engine - or more precisely, a central component of it—the camshaft. In four-stroke engines (and in



Om the left: CAD design of the fully variable valve train.
Below: 1.4 litre four-cylinder gas engine with the fully variable valve train on the Empa engine test bench in Dübendorf.
Illustrationen: Empa



some two-stroke engines), the camshaft actuates the valves that control the entry of air into the combustion cylinders and later the exit of exhaust gases. In Empa›s development, the function of the camshaft is performed by an electrohydraulic valve train, which eliminates the need for the throttle valve, which is traditionally used and is subject to losses. The advantage of the new valve train is that it enables flexible control of the intake and exhaust valves. This paves the way for new engine concepts - for example, an engine that functions as a two-stroke when accelerating and as a four-stroke engine during normal driving. Because passenger car engines operate a significant part of the time in the low load range, the new valve train contributes particularly to efficient and thus fuel-saving operation. It also promotes the use of new types of fuel, such as renewables. The valve train does not use oil as a hydraulic fluid, but a water-glycol mixture. In this way, the amount of additives to the engine oil added can be reduced, which benefits the longevity of the catalytic converter and saves costs.

The Empa researchers have demonstrated the advantages of the fully flexible valve train in a functional model, and have applied for corresponding patents. Empa is currently running a follow-up project (‘FlexWork’) in which the valve train is used in an spark ignited engine powered by methane. “Thanks to the new project, we will be able to quantify the efficiency advantage of the flexible valve train,” says Empa researcher Dr. Patrik Soltic. The scientist estimates a reduction in fuel consumption of at least 10% compared with a conventional camshaft valve train. An industrial partner is currently being sought who is willing to take up the challenge of using the new valve train to build an innovative gasoline engine without the well-established camshaft. If this succeeds, it may be possible to repeat a Swiss success story: In the 1980s, the then ETH researcher Wolfgang Schneider was instrumental in the development of common rail injection that is now widely used in diesel engines and enables more flexible and economical operation. The same Wolfgang Schneider and his engineering team also contributed to the development of the new valve train.

- The **final report** of the project ‘NextICE - Next Generation of Alternative Fuel Converters in the Transportation Sector’ can be found at:
https://www.aramis.admin.ch/Texte/?ProjectID=34728

- **Information** on the project can be obtained from Dr Carina Alles (carina.alles[at]bfe.admin.ch), head of the SFOE’s combustion-based energy systems research programme.

- Further **articles** on research, pilot, demonstration and flagship projects in the field of mobility can be found at www.bfe.admin.ch/ec-mobilitaet.

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