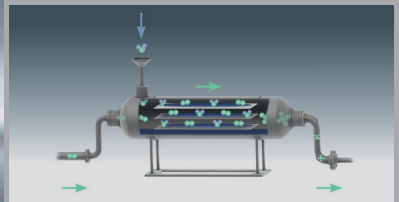


Audi e-gas-project

Life Cycle Assessment





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Motivation

Ecology and economy in harmony: this is the biggest challenge we will face in the future. If we are to succeed, we must achieve equilibrium in the entire field of mobility – including human beings, their new values and their environment. Our objective is CO₂-neutral mobility.

(Rupert Stadler, Audi CEO)



We have arrived at a decisive point in the energy transition: Audi is launching production of climate-friendly fuels for mobility of the future.

In the German city of Werlte in Lower Saxony, the world's first industrial plant has been launched to produce synthetic gas based on the power-to-gas principle. A natural gas substitute – Audi e-gas – is being created there from renewable electricity, water and carbon dioxide. Distributed through the natural gas grid, e-gas is available at more than 600 filling stations throughout Germany to drivers of the A3 Sportback g-tron.

Because e-gas production results in a closed carbon dioxide cycle, e-gas drivers can travel long or short distances while remaining carbon-neutral.

In order to assess the environmental impact of Audi e-gas and the A3 Sportback g-tron over the entire life cycle, Audi has compiled life cycle assessments that have been validated by TÜV Nord. The results are presented in this booklet.



Life cycle assessment – what's involved

The life cycle assessment analyses the effects of a product on the environment during its entire existence, from production through its period of use and its end-of-life recycling. It is a quantitative evaluation of ecological aspects such as the emission of greenhouse gases (including carbon dioxide [CO₂]), energy consumption and acidification or 'summer smog'. Audi compiles its life cycle assessments according to the procedure laid down in the international ISO 14040 series of standards.

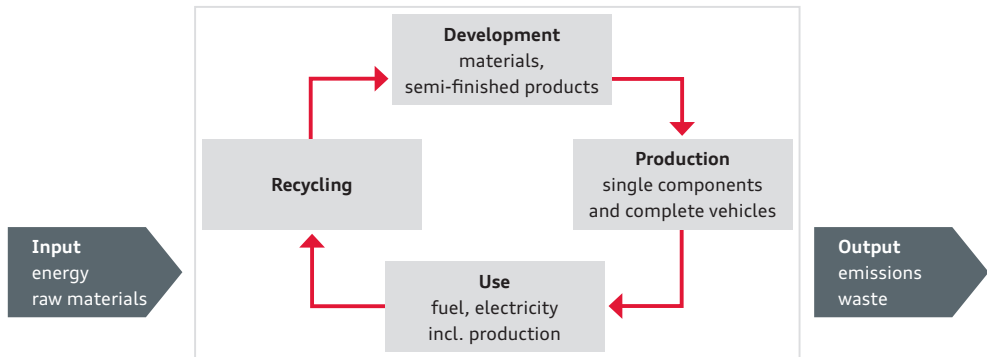
Life cycle assessment of vehicles as a major contribution to more sustainable treatment of the environment



Dimensions of assessment:

- ▶ **Development phase:** materials and semi-finished product manufacturing chains
- ▶ **Production phase:** components and complete vehicles
- ▶ **Use phase:** fuel/ electricity (including production)
- ▶ **Recycling phase:** process chains to recover valuable materials

Stages in motor vehicle life cycle assessment



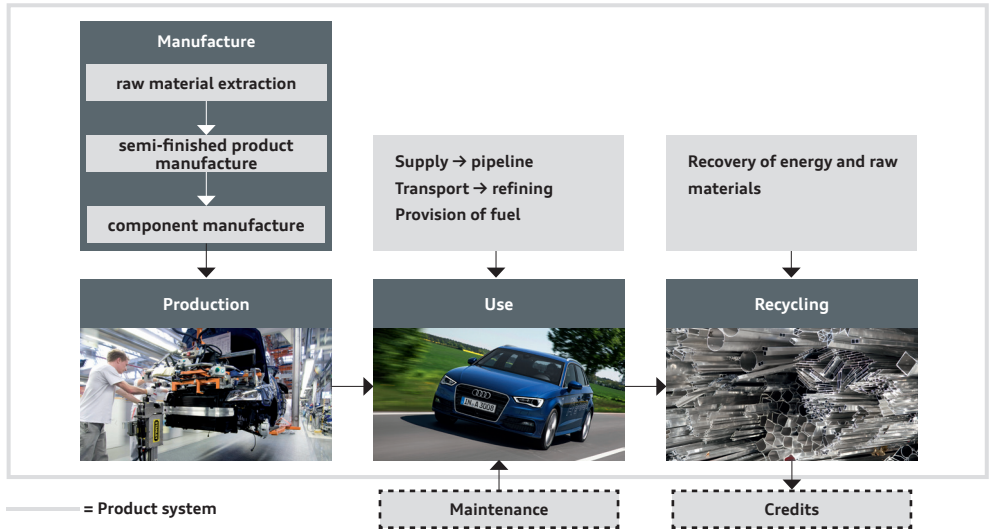
Life cycle assessment – the boundaries

Before a life cycle assessment is compiled, its boundaries must be defined by deciding which processes should be examined. The available means, the time framework and data availability all have to be taken into account. Audi has laid down broad limits for its complete vehicle life cycle assessments.

The examination starts with the manner in which raw materials are obtained, and how individual components are manufactured. Even during the first new model development stages, the engineering teams have to make decisions that have a major impact on in-house production and the entire supply chain.

Audi's experts assume for assessment purposes that vehicles will cover a distance of 200,000 kilometres. They not only take into account the emissions caused when the vehicle is being driven, but also those that occur when the fuel is produced. At the end of the vehicle's life cycle, the energy needed for recycling is also included in the assessment.

System boundaries of total vehicle LCA

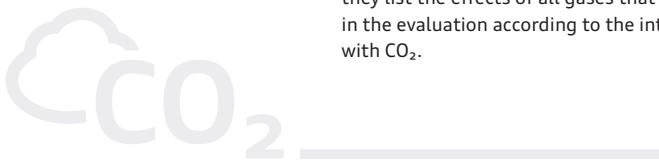


Life cycle assessment – effect categories

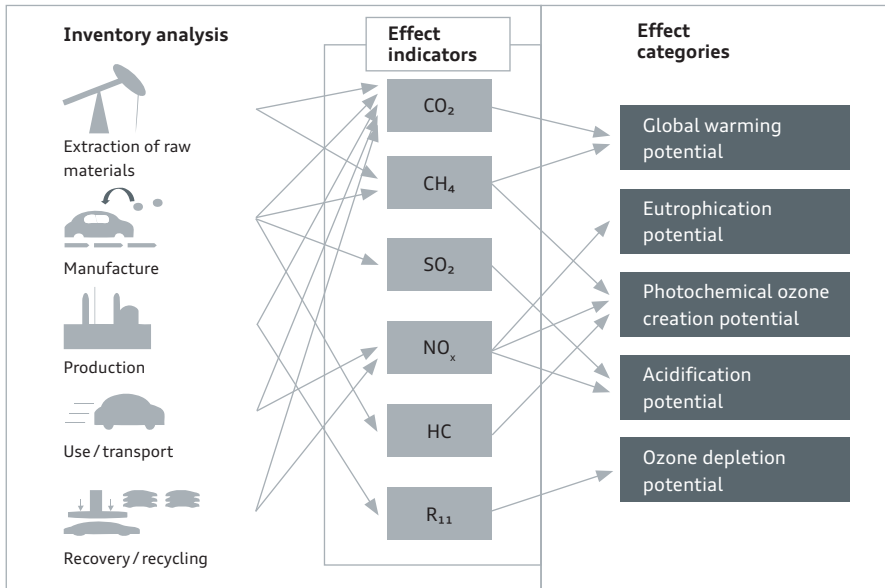
The main emphasis in life cycle assessments is currently the evaluation of greenhouse gases. But Audi is also carefully monitoring other environmental effects as well: eutrophication of water and soil, creation of summer smog, acidification of eco-systems and the damage to the ozone layer.

In accordance with the procedure laid down in the ISO 14040 standard, the results from data collection (inventory analysis) are converted into effect indicators, which are then grouped together in effect categories.

The effect categories describe the major ecological problem areas. When Audi's specialists assess the greenhouse effect as an important indicator, they list the effects of all gases that affect the climate. These are included in the evaluation according to the intensity of their effect as compared with CO₂.



Effect of substances on the environment



Audi e-gas project

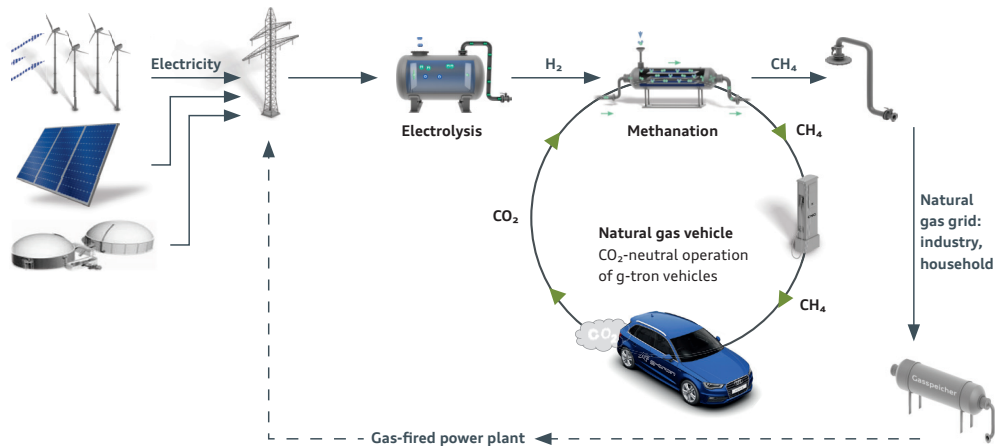
The future of Germany's power supply belongs to renewable sources of energy. The production of electricity via wind and sun, however, is subject to natural fluctuations and the necessary storage capacity is currently very low.

The concept for the Audi e-gas project is an important component of the energy transition because it answers the open question of how renewable electricity can be stored independent of location and for long periods. Aside from its use as a fuel for natural gas-powered cars, reconvertng e-gas during periods with little wind and sun is also possible. The natural gas grid with its unrivaled capacity then functions as a very large buffer storage network and can deliver the energy to precisely where it is currently needed.

The Audi e-gas plant in Werlte is the world's first that systematically puts power-to-gas technology – linking the electricity and natural gas grid – into practice. This opens up completely new possibilities and can provide strong impetus to the expansion of renewable energies.

In this way, the mobility options with the CNG car Audi A3 g-tron and climate-neutral Audi e-gas fuel are both a part and a driving force in the energy transition.

Electricity is transformed through electrolysis and methanation into synthetic methane – known as Audi e-gas.



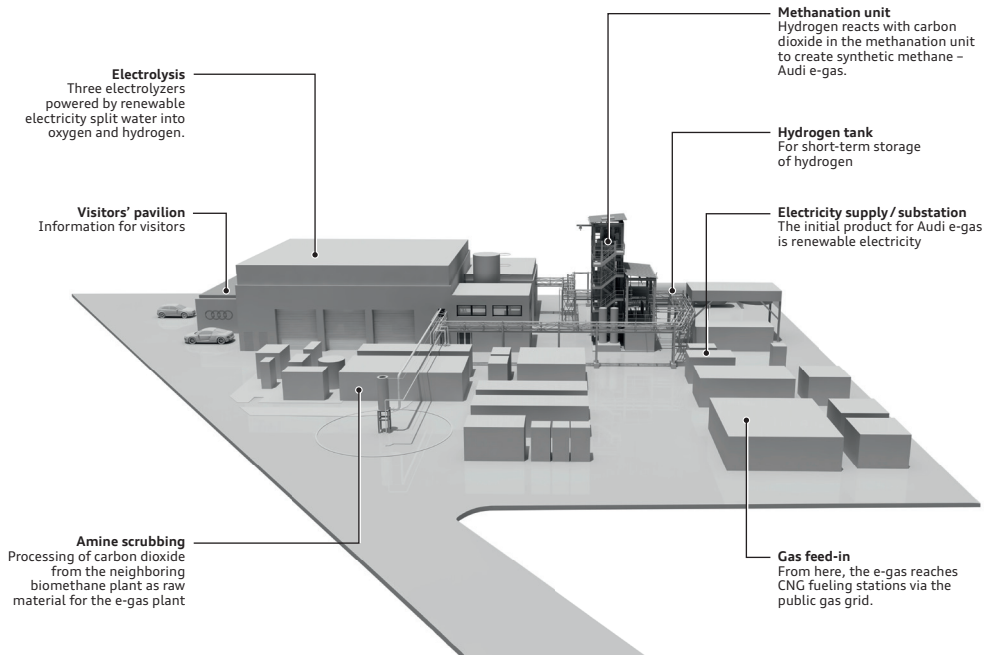
Audi e-gas plant

The Audi e-gas plant in Werlte, which was developed in partnership with the equipment manufacturer ETOGAS GmbH, is operated with renewable electricity (such as from wind or sun). The plant, with a power capacity of around 6,000 kW, will primarily draw electricity if there is excess supply in the electricity grid and, for instance, wind turbines have to be shut off.

In a first step, the electricity is transferred to three electrolyzers that split water into its components: oxygen (O_2) and hydrogen (H_2). At this point, the hydrogen can be removed if needed and used, for example, for future fuel-cell cars.

The required hydrogen supply infrastructure is currently lacking, however, and hydrogen can only be fed into the existing natural gas grid to a very limited extent. Audi solves this problem with another innovative processing step: combining hydrogen with carbon dioxide (CO_2) in the methanation unit produces synthetic renewable methane (CH_4) – Audi e-gas. This natural gas substitute can be fed at the site into the natural gas grid and thus can be stored.

The e-gas plant acquires the CO_2 required for methanation from the flow of exhaust gas from the neighboring biomethane plant of electric utility company EWE. There, the CO_2 is separated from the raw biogas in order to produce pure biomethane by means of amine scrubbing.

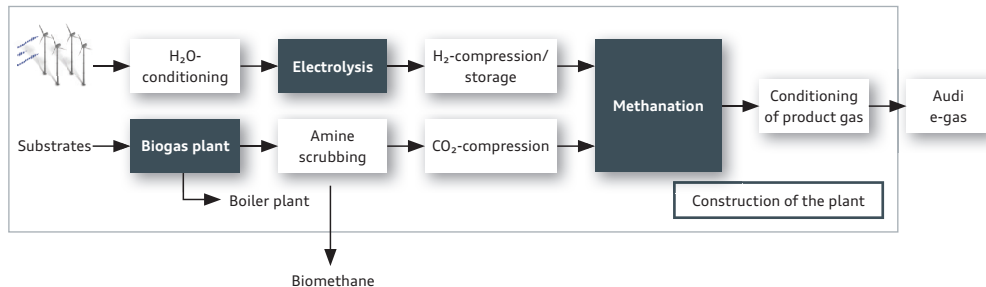


Audi e-gas – the results of the life cycle assessment

For the production of Audi e-gas, Audi has compiled a life cycle assessment on the current project status. Verification and refinement of the assessment is planned after successful startup of operation.

In addition to the actual Audi e-gas plant, the system boundaries of the life cycle assessment include the biogas plant and amine scrubbing as a source of CO₂.

System boundaries

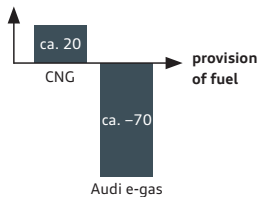


To analyze the life cycle assessment for the production of Audi e-gas, the same impact categories are observed that are drawn upon in the total vehicle LCA.

With respect to greenhouse gas potential, fossil fuel-derived natural gas emits approx. 20 g CO₂/km* in the production of fuel (well-to-tank). Using the same evaluation method for the Audi e-gas and taking the intake of CO₂ in the production into consideration results in a value in the range of -70 g CO₂/km*. See page 26 for more details.

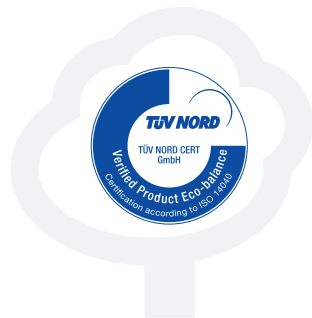
The table shows the other impact categories. Audi e-gas causes lower emissions than fossil fuel-derived natural gas in every category except acidification potential, which is primarily due to the manufacturing of materials for the plant. However, with regard to absolute value, this increases to a non-relevant range.

Global warming potential
CO₂-equivalents [g/km]



Result of assessment – Audi e-gas compared to fossil fuel-derived natural gas

Eutrophication potential	-20 %
Ozone depletion potential	-30 %
Photochemical ozone creation potential	-43 %
Acidification potential	+81 %



* assumed fuel consumption: 3,2 kg CNG/100 km; CO₂ emissions: 88 g/km

Impressions of the official opening ceremony of the Audi e-gas plant in Werlte



The three electrolyzers (pictured above) are the first step in producing Audi e-gas. Water is split into its two components: hydrogen and oxygen.



In the methanation unit (centre picture), the hydrogen is converted into synthetic methane by adding CO₂.

This CO₂ has already been separated from raw biogas coming from the neighboring biogas plant by means of amine scrubbing (pictured below).



Guests of the opening ceremony included (from left to right):
Reiner Mangold, Head of Sustainable Product Development and e-fuels at AUDI AG,
Dr. Michael Specht, Head of the Department for Renewable Energies and Processes at ZSW Baden-Württemberg,
Heinz Hollerweger, Head of Total Vehicle Development at AUDI AG,
Prof. Dr. Willi Diez, Director of the Automotive Industry Institute,
Jochen Flasbarth, German Environmental Protection Agency



The Audi A3 Sportback g-tron has been available since the beginning of 2014. In pure e-gas mode the g-tron is entirely CO₂-neutral.

Audi A3 Sportback g-tron

The Audi A3 Sportback g-tron has been available since the beginning of 2014. This bifuel five-door compact car based on the new A3 1.4 TFSI features a maximum output of 81 kW (110 hp) and uses carbon-neutral Audi e-gas to realize CO₂-neutral mobility.

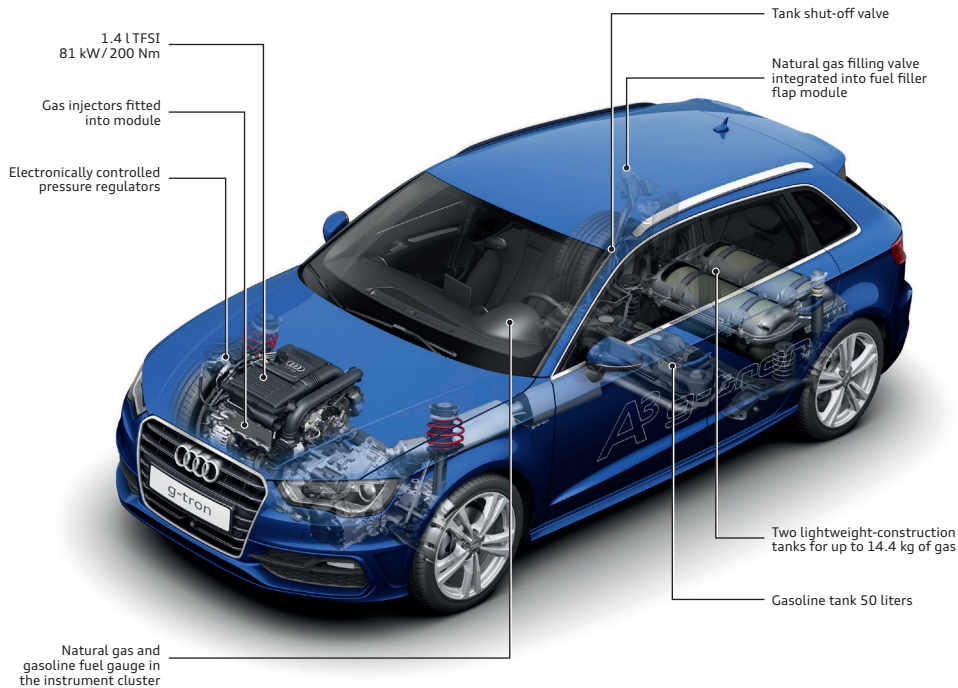
The CNG car uses an average of 3.2 kilograms* of Audi e-gas or natural gas per 100 kilometers and has a range of about 400 kilometers (~250 miles). If the natural gas pressure sinks below 10 bar, the engine management system automatically switches to gasoline-powered operation, which provides an additional range of 900 km (~560 miles). This means the total range is therefore roughly the same as the Audi A3 TDI.

Customers who drive the Audi A3 Sportback g-tron will be able to purchase the amounts of Audi e-gas they draw from public CNG fueling stations via an invoicing method like that for purchasing green electricity. The precise principle is explained on the following page.

The A3 Sportback g-tron features the latest natural gas engine technology, starting with the storage of the fuel. The two tanks located under the luggage compartment floor can each store seven kilograms of gas at a maximum of 200 bar. In keeping with the lightweight construction philosophy, each tank weighs 27 kg less than a conventional tank made of steel. This is primarily thanks to the use of carbon- and glass-fiber reinforced plastic, which also ensures maximum strength and protection from damage.

A life cycle assessment examined the impact of using fiber-reinforced plastics in the car's tanks on emissions during production and the impact of Audi e-gas on the use of the A3 g-tron. Results of the assessment are presented from page 24 onwards.

* Fuel consumption acc. to NEDC: Audi A3 Sportback 1.4 g-tron 81 kW (MY 2014): fuel consumption combined: 3,2 kg CNG/100 km; CO₂ emissions 88 g/km



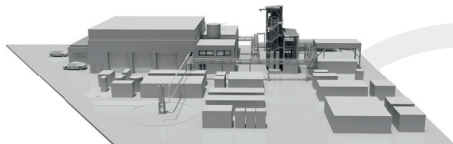
Audi e-gas fuel card

With Audi, customers are driving into an eco-friendly future and actively helping to shape and promote the energy turnaround. With the Audi e-gas fuel card from Audi Leasing, customers can fill up their Audi A3 g-tron with Audi e-gas and stay climate-neutral as they drive.

The Audi e-gas fuel card is available for a fixed monthly sum (Audi e-gas premium), which is invested in further technological advances. The local Audi partner will help you with any questions about the Audi e-gas fuel supply agreement. It points the way to eco-friendly mobility, which Audi makes possible for its customers in cooperation with Audi Financial Services and DKV Euro Service GmbH & Co. KG.

The principle is simple (see illustration on the right): Audi records the quantities of e-gas that have been paid for with the Audi e-gas fuel card and consumed, and feeds precisely the same quantity back into the German natural gas grid in Werlte.

Principle of the Audi e-gas fuel card



Feeding of the purchased quantity
into the gas grid

Audi e-gas plant
in Werlte



Customer fills up with e-gas
using the e-gas fuel card

Transmission of the
purchased quantity



Audi A3 Sportback g-tron – the life cycle assessment



Audi has produced a detailed life cycle assessment for the Audi A3 Sportback g-tron. It compares the Audi A3 Sportback 1.4 g-tron 81 kW with the gasoline-powered Audi A3 Sportback 1.4 TFSI 90 kW; both cars feature the 7-speed S tronic automatic transmission.*

In this life cycle assessment for the A3 Sportback g-tron, the life cycle assessment compiled especially for Audi e-gas was used for the upstream fuel supply chain during the car's service life.

Audi also examined operation of the A3 g-tron with fossil fuel-derived natural gas.

* Fuel consumption acc. to NEDC:

Audi A3 Sportback 1.4 TFSI 90 kW (MY 2014): urban 6,1 l/100km; country 4,3 l/100km; combined 5,0 l/100km;
CO₂ emissions: 116 g/km; energy efficiency category B

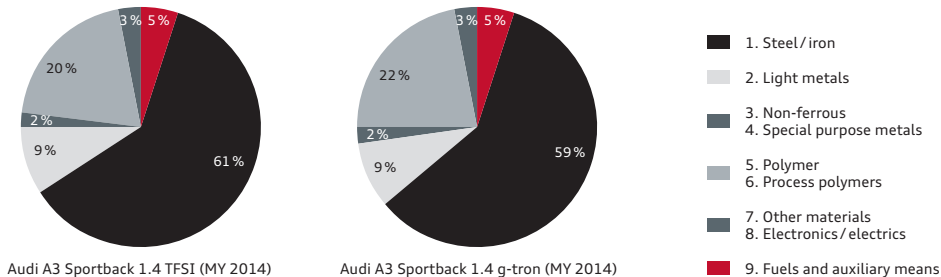
Audi A3 Sportback 1.4 g-tron 81 kW (MY 2014): urban 4,1 kg CNG/100 km; country 2,7 kg CNG/100km; combined 3,2 kg CNG/100km;
CO₂ emissions: 88 g/km; energy efficiency category A+

Audi A3 Sportback g-tron – the production phase

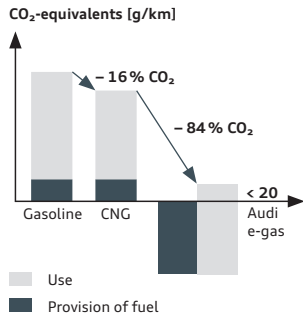
The materials used in production have a major impact on the results of the life cycle assessment. The composition of materials used in the examined models was determined and compiled in accordance with VDA guidelines 231-106.

The gasoline-powered model and the natural gas version of the Audi A3 Sportback differ only in the polymer materials and the steel and iron materials.

Through the use of fiber-reinforced plastics for the gas tanks of the Audi A3 Sportback g-tron, the proportion of the polymer materials in this model increased to 22 % compared with 20 % in the gasoline-powered model. In contrast, fewer steel and iron materials are used in CNG vehicles, relatively speaking.



Audi A3 Sportback g-tron – the use phase



The environmental benefit of Audi e-gas becomes even more significant in a well-to-wheel comparison (fuel supply process including use) with other fuels. The diagram shows the savings of greenhouse gas emissions of Audi e-gas in comparison to gasoline and fossil fuel-derived natural gas (CNG).

In the production of Audi e-gas, the acquisition of CO₂ from the biogas plant is indicated negatively. These emissions, if not used in Audi e-gas, would be emitted into the air. During driving operation, the CO₂ now bound into Audi e-gas is emitted again during the combustion process in the car. This represents a closed CO₂ cycle.

The CO₂ emissions that are not a part of the cycle occur, above all, through the energy expenditure and material input for the construction and operation of the wind turbines and the Audi e-gas plant. Based on current modelling, CO₂ emissions are under 20 g/km.

well-to-wheel emissions of an Audi A3 Sportback g-tron
powered by Audi e-gas



< 20 g CO₂/km*

* Fuel consumption acc. to NEDC:

Audi A3 Sportback 1.4 g-tron 81 kW (MY 2014): fuel consumption combined: 3,2 kg CNG/100 km; CO₂ emissions 88 g/km

Audi A3 Sportback g-tron – the entire life cycle

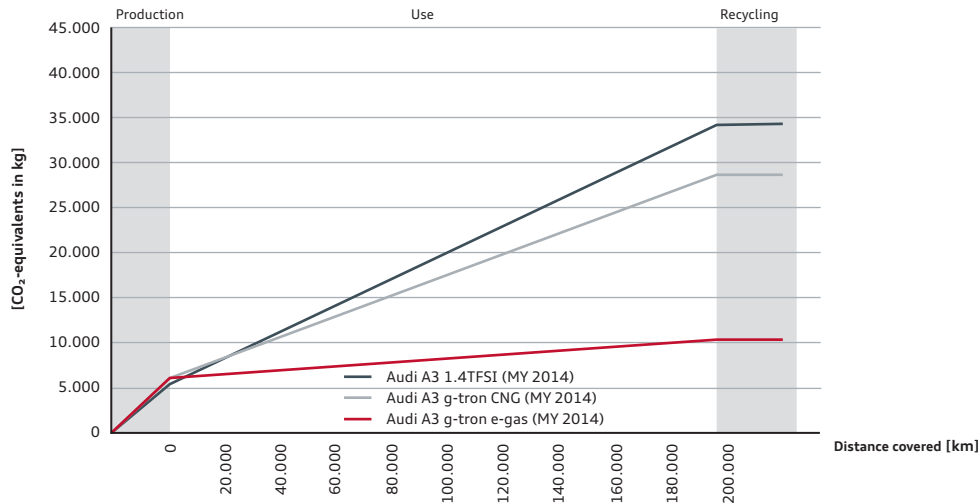
When considering the entire life cycle, the Audi A3 Sportback g-tron exhibits higher emissions during production than the gasoline-powered comparison model, which is due to high energy requirements during production of the g-tron's lightweight gas tanks. However, the break-even point when using Audi e-gas is already reached at just over 5,000 km. Even when powered with fossil fuel-derived natural gas, the additional expenditures during the production process are amortized at below 22,000 km. From this point, the higher energy content of the natural gas and the associated lower consumption of the CNG car has a positive impact, with each kilometer, on the assessment.

While the Audi A3 Sportback 1.4 TFSI generates the equivalent of about 34 t CO₂ throughout the entire life cycle, less than the equivalent of 29 t CO₂ are generated by the Audi A3 Sportback g-tron with fossil fuel-derived natural gas. Using Audi e-gas as a fuel can even reduce greenhouse gas emissions by almost 70 %, to the equivalent of about 10 t CO₂, across the entire life cycle.

The Audi A3 Sportback g-tron also achieves better results than the gasoline-powered model in all other impact categories observed. The only exception is in ozone depleting potential, to which primarily the high electricity demand for compression of the gas at the filling station contributes. For the calculation the European grid mix is used. With the expansion of renewable energies this value will decrease gradually.

Result for entire life cycle – in comparison with gasoline	Fossil fuel-derived natural gas	Audi e-gas
Global warming potential	-16 %	-70 %
Eutrophication potential	-26 %	-27 %
Ozone depletion potential	+20 %	+20 %
Photochemical ozone creation potential	-21 %	-25 %
Acidification potential	-25 %	-14 %

Greenhouse gas emissions from the A3 Sportback models analyzed across the entire life cycle



The additional expenditures especially due to the use of fiber-reinforced plastics in the gas tanks are already amortized at just over 5,000 km (Audi e-gas) or within the first 22,000 km (fossil fuel-derived natural gas).

CNG tank recycling concept

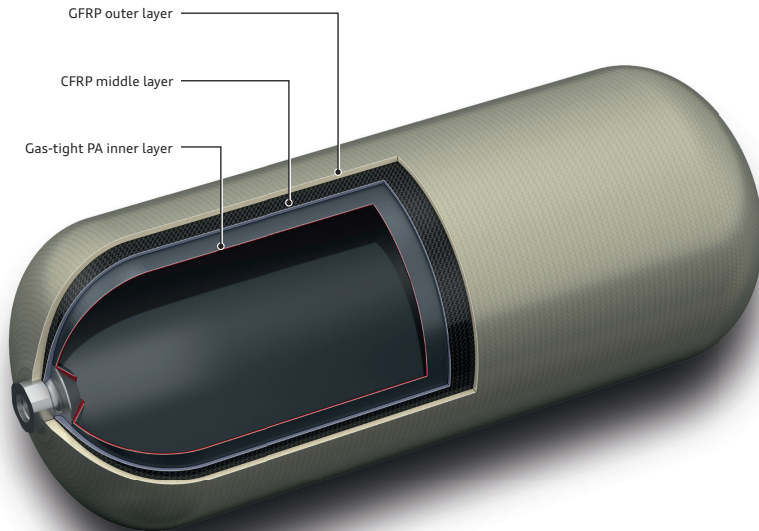
The production of carbon fiber as well as its processing into carbon fiber-reinforced plastics (CFRPs) in components is highly energy-intensive and results in higher greenhouse gas emissions. In addition, significant scrap waste is generated during the production process.

Audi has developed a concept for recycling the CNG tanks in order to reduce the emissions and to continue utilizing the excellent mechanical properties of carbon fiber.

In accordance with national regulations, CNG tanks must be dismantled by authorized personnel and all residual methane removed with nitrogen washes. This regulation also simplifies the feeding of the tanks back into the recycling process, starting with the shredding of the tanks into small pieces that can be fed into pyrolysis. In pyrolysis, all materials adhering to the carbon fibers are then removed and are available after the process as recycled fiber. Through various processing steps, new semi-finished products are manufactured that can already be employed in components that do not have structure-related requirements.

Yet this was still not enough to satisfy the engineers at Audi. They are currently researching the reintroduction of recycled carbon fibers into components that are subjected to higher mechanical loads. The challenge here is to retain the excellent mechanical properties of the carbon fiber during the recycling process and to substitute new materials with the reclaimed fibers.

Composition of the lightweight CNG tanks



Conclusion

We view the examination of environmental influences across the entire life cycle of a car as one of our most important tasks for the future. The public currently judges cars based on their fuel consumption. Audi looks one step ahead, using life cycle assessments to analyze the entire life cycle of a car including fuel production.

The Audi e-gas project demonstrates clear environmental advantages over fossil fuel-derived natural gas. Aside from storing renewable energies in the form of synthetic methane combined with an infrastructure that is already in place, over 80 % of the greenhouse gas emissions can be reduced through the use of Audi e-gas.

The major issues of our time – the increasing scarcity of raw materials and the increase in greenhouse gases – can only be responded to with a broadly designed approach.

The life cycle assessment of the Audi A3 g-tron with the Audi e-gas project demonstrates how future carbon-neutral mobility can be designed.

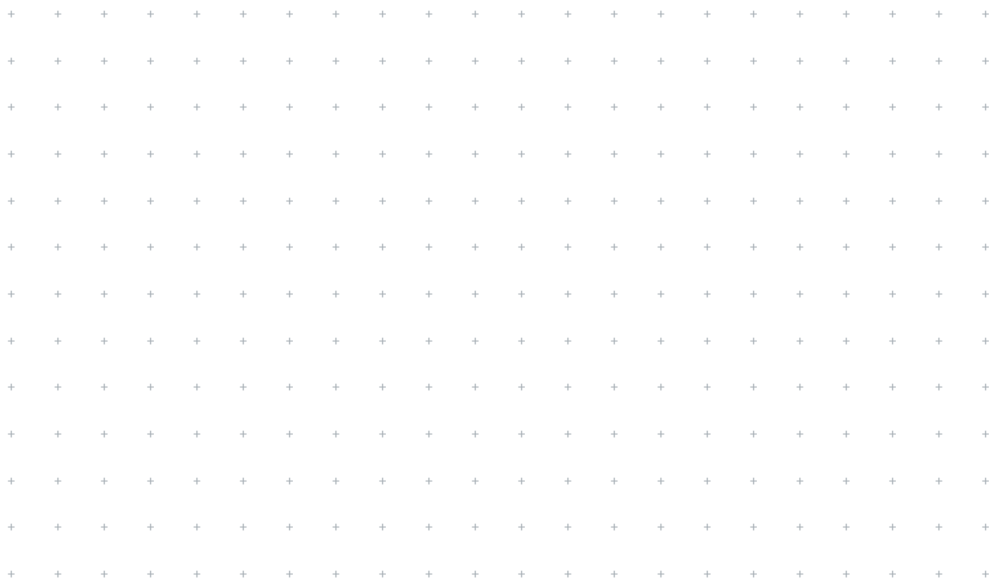
For further information and the latest developments, go to:
<http://www.audi-future-lab-mobility.com/>



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This booklet was made from chlorine-free bleached pulp and is part of a climate-neutral printing process.

