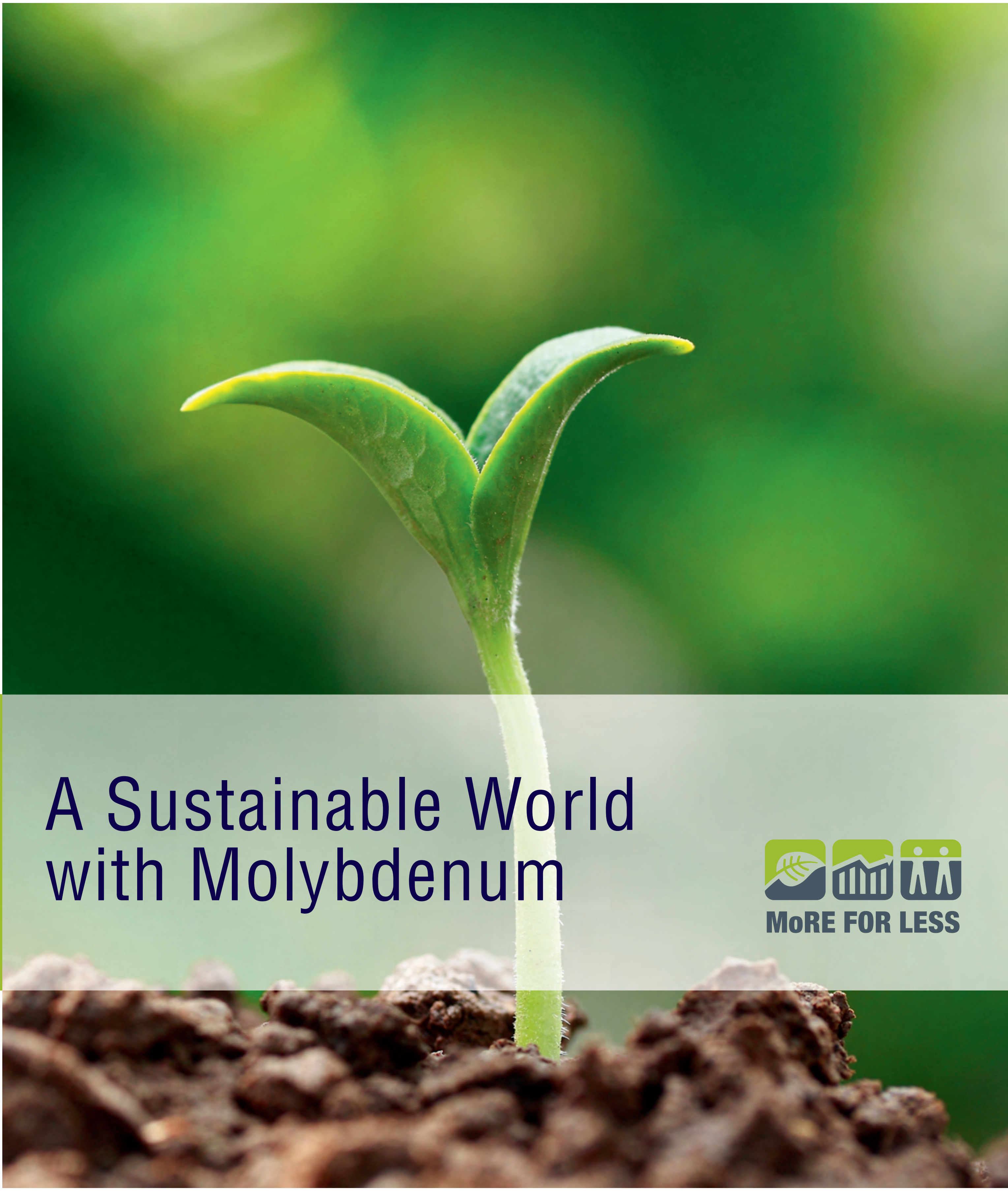
IMOA

INTERNATIONAL MOLYBDENUM ASSOCIATION
THE VOICE OF THE MOLYBDENUM INDUSTRY



A Sustainable World with Molybdenum

MoRE FOR LESS

www.imoa.info

A sustainable world with molybdenum

First edition 2015

ISBN 978-1-907470-35-6

Published by the International Molybdenum Association (IMOA), London, UK
www.imoa.info info@imoa.info

Designed by circa drei, Munich, Germany

Images courtesy of iStockphoto.com/bo1982 (cover), iStockphoto.com/PhotoInc (p. 3), shutterstock.com/OliverSved (p. 4), iStockphoto.com/MichaelKnudsen (p. 5 left), Steffian Bradley Architects (p. 6), Iwan Baan (p. 7), Scania CV AB (p. 8), wikipedia commons/Dergenaue/CC-BY-SA-2.0-DE (p. 9), iStockphoto.com/fotoember (p. 12 left), Wikipedia commons/user:wutzofanti (p. 12 right), iStockphoto.com/Rebell (p. 13), Manz AG (p. 14), PVTech (p. 15), John Grocki of Advantage Resources Consulting (p. 16), Haldor Topsøe (p. 17 top), TonyV3112/shutterstock.com (p. 17 bottom), rob245-fotolia (p. 18), iStockphoto.com/espiegle (p. 20), Cronimet (p. 21), Esko Keskioja (p. 22), Zephyr/Science photo library (p. 24), Linleo-fotolia (p. 25), medmovie.com (p. 26), IDE Technologies (p. 27)

The context

The Intergovernmental Panel on Climate Change (IPCC) continues to conclude that increasing concentrations of carbon dioxide and other greenhouse gases (GHGs) from human activity are responsible for global warming. It is widely accepted that the resulting increase in the average global temperature has led to climate change, which will become more significant in the future unless GHG emissions are mitigated.

Global energy demand is expected to grow by more than one-third in the next 25 years. World population exceeded seven billion in 2013, increasing the pressure on natural resources. The environmental challenges posed by our modern lives have never been greater.

ECOLOGY

ECONOMY

SOCIETY

The concept of sustainable development is that the earth's resources are used to meet human needs in such a way that the environment is preserved and protected for present and future generations. The three main pillars of sustainable development are widely recognized as Ecology, Economy and Society. Ecology considers impacts such as environmental performance, resource use, recycling, and energy efficiency and production, while Economy examines dimensions affecting cost such as the supply chain, life cycle and materials performance. The Social pillar covers contributions including health, safety and wellbeing.

Molybdenum (Mo) is usually added to other materials, typically in very small quantities, to make a big difference to the performance of the end product. MoRE FOR LESS is a way of demonstrating the many ways in which molybdenum contributes to sustainable development and how its use as a metal, as an alloying element, and as a constituent of chemical products benefits modern society, the environment and the economy.

Natural and life sustaining

Discovered in the 18th century, molybdenum is a naturally occurring element, found in the earth's crust and within our bodies. In fact, it's essential for all human, animal and plant life.

In humans, molybdenum activates enzymes with antioxidant properties, helping to rid the body of free radicals which can lead to disease. Molybdenum is also associated with enzymes responsible for regulating waste removal, helping to metabolize toxins and the byproducts of digestion. It also plays a crucial role in the biochemical processes responsible for energy production, quite literally keeping us alive.

Molybdenum is essential for the metabolism of amino acids and for the production of other enzymes in animals. Added dietary molybdenum can also stimulate growth in some animals.

In plants, it is essential for the production of two major enzymes that play a key role in 'fixing' nitrogen from the soil and air for making amino acids, proteins and chlorophyll. Some soils require supplemental molybdenum to support healthy plant life, boosting production in agricultural crops by up to 60%.

Unique properties

Molybdenum has several unique properties that hold the key to its sustainable development credentials.

In low alloy steels, molybdenum improves strength and hardness, maintains toughness and increases high temperature strength. The strengthening effect makes it ideal for use in lightweighting applications, such as in the design of more fuel-efficient cars and trucks. Lighter but stronger steel construction saves the quantity of materials and energy required for the production, transportation and fabrication of pipelines, bridges and buildings. The hardening effect increases durability and longevity in high-wear applications and ensures that critical components in machines and tools last longer.

In stainless steels, molybdenum increases corrosion resistance, ensuring longevity in many uses within architecture, building and construction, process industries, power generation, water treatment and distribution, and other sectors. In nickel-based alloys, molybdenum contributes to high temperature strength and increases corrosion resistance, enabling the operation of fossil fuel power plants at higher temperatures and pressures, greatly increasing their efficiency and reducing carbon emissions.

Molybdenum is also used in a variety of industrial chemicals and catalysts, including those needed for the production of low sulfur vehicle fuel.

Energy efficiency

Global energy demand is expected to grow by more than one-third in the next 25 years. Approximately 25% of global emissions of greenhouse gases (GHGs) arise from electricity generation. To even come close to meeting this demand while implementing the substantial and sustained reductions of GHGs necessary to tackle climate change will require an entirely new approach to using energy more efficiently.

Sunscreens

Air conditioning accounts for the majority of energy consumption in many buildings. Sunscreens offer a solution to the problem of passive solar heat gain, reducing or even eliminating the need for air conditioning. If selected correctly, molybdenum-containing stainless steel is an ideal material for the screens, guaranteeing corrosion resistance and decades of low-maintenance performance, even in coastal or pollution-prone industrial and urban areas.

The Federal Building in San Francisco, U.S., was designed to use dramatically less energy than conventional office buildings, incorporating a 'skin' of molybdenum-containing Type 316 stainless steel sunscreen panels, linked to a control system using natural ventilation for cooling. As a result, the Federal Building uses one-third of the energy typically consumed by a Californian office block.

Type 316 stainless steel was also utilized at the Guangzhou Children's Activity Centre in China, pictured below, to construct a passive sunscreen in a seamless, curving design. The woven mesh screen is supported on a lightweight frame, maximizing natural light within the building and removing the need for air conditioning in communal areas.

Molybdenum-containing stainless steel sunscreens reduce the need for air conditioning

Case study in brief
Federal Building

The U.S. Government's General Service Administration wanted the new Federal Building in San Francisco to use dramatically less energy than conventional office buildings over a design life of 100 years.

Solar heat gain is traditionally remedied with air conditioning, greatly contributing to a building's overall energy demands. The designers of the Federal Building worked with thermal performance experts and instead specified a sunscreen to reduce heating, manufactured from molybdenum-containing Type 316 stainless steel to increase resistance to corrosion.

Only the first few floors of the building are air conditioned. The rest is cooled using natural ventilation, controlled by a sophisticated system that opens and closes windows and vents and moves the sunscreen panels in response to environmental conditions.

The result is a building that consumes one-third of the energy required by conventional office accommodation.

The specification of molybdenum-containing stainless steel helps to guarantee its design life of 100 years with low maintenance requirements, despite the corrosion challenges posed by its coastal, urban location.

ECOLOGY ECONOMY SOCIETY

For further information, please see the full case study in the sustainability section of the IMOA website: http://www.imoa.info/download_files/sustainability/IMOA_Federal_13.pdf

High-strength steels containing molybdenum are used in cars and trucks to make lighter, more fuel-efficient vehicles

Automotive use

Cars and trucks are responsible for nearly 20% of global CO_2 emissions, making road transport an important greenhouse gas target. Reducing the weight of a vehicle by 100 kg saves between 0.1 and 0.5 liters of fuel per 100 kilometers, equating to a reduction of 8 to 12 grams of CO_2 per kilometer.

High-strength steel (HSS) has progressively replaced mild steel in car bodies and chassis, enabling weight reductions of 20 to 25%. Ultra high-strength steels have the potential to reduce weight by a further 20%. Molybdenum allows the production of steel with exceptional strength and good formability. Of all suitable alloying elements, molybdenum has the most effect per added percentage by weight and has no negative effect on zinc galvanization. It also provides excellent hardenability in increasingly popular press-hardening steel, improving component behavior in crash conditions.

Power generation

Coal-fired generation is predicted to supply nearly half of global capacity by 2030. These power stations emit the most CO_2 per kWh, therefore reducing their emissions is an important environmental priority.

Increasing thermodynamic efficiency by burning coal at higher temperatures reduces CO_2 emissions. However, higher boiler temperatures can only be sustained with appropriate materials. High temperature creep can otherwise lead to deformation and premature failure of components, which are also at risk from the highly corrosive environment inside a typical fossil fuel boiler.

Nickel-based alloys containing molybdenum have sufficiently high creep strength and excellent resistance to steam-side oxidation, enabling power stations to run at higher temperatures and pressures, increasing their efficiency, conserving resources and reducing CO_2 emissions.

Case study in brief

Supercritical and ultra-supercritical power plants

Power plants are defined as subcritical, supercritical and ultra-supercritical (USC), depending on their operating temperature and pressure. Most coal-fired power plants are subcritical and run at less than 35% efficiency. Some supercritical plants and the first USC plants reach efficiencies of around 45%, while future plants operating at 700°C or more are expected to achieve 50% efficiency.

Increased temperatures can only be sustained with specialized materials that can resist heat deformation. Ferritic steels alloyed with molybdenum are commonly used in subcritical applications, providing sufficient strength up to about 500°C. Bainitic and martensitic steels with higher amounts of molybdenum are used at temperatures up to 650°C. At temperatures exceeding 700°C, only specialist 'superalloys' containing nickel and molybdenum have the required strength and resistance to oxidation and corrosion from the combustion process.

It is estimated that increasing average efficiency from 35% to 50% globally could reduce CO_2 emissions by as much as 40%. Molybdenum is an essential ingredient in the alloys that will allow future USC power stations to achieve these efficiencies.

ECOLOGY ECONOMY SOCIETY

For further information, please see the full case study in the sustainability section of the IMOA website: http://www.imoa.info/download_files/sustainability/IMOA_Supercritical_and_Ultra-supercritical_Power_Plants.pdf

Heat-resistant steels and nickel alloys containing molybdenum allow higher combustion temperatures in fossil fuel power plants, increasing efficiency and reducing carbon emissions

Case study in depth

Ford Fusion B-Pillar

The challenge

The past two decades have seen growing pressure on vehicle manufacturers to reduce the environmental impact of their vehicles. The EU estimates that around one-fifth of the region's greenhouse gas emissions come from road transportation. In China, the world's largest vehicle market, concerns over air pollution in urban areas have seen significant emission controls introduced, leading to the adoption of standards equivalent to the Euro IV emissions standard. At the same time, fuel efficiency is an increasingly important consideration.

The solution

One of the most effective ways to improve fuel efficiency and lower emissions is to reduce the mass of the vehicle, a process known as lightweighting. Advanced high-strength steels (AHSS) combine higher concentrations of alloying elements with innovative production techniques to make stronger steel with lower mass while offering equal strength and crash resistance.

How molybdenum can help

Molybdenum plays a key role as an alloying element in many AHSS grades, ensuring that vehicle components can be made lighter and stronger, while remaining economically competitive.

Redesigning the B-Pillar

A vehicle's B-Pillar is one of the most critical body components, protecting the occupants and helping to maintain structural integrity during a side impact, as shown in **figure 1**.

In designing the new Fusion model, Ford's development team aimed to produce a body structure with class-leading safety while reducing the overall mass. The previous press-hardened boron steel B-pillar was replaced with a hydroformed part made from a mix of DP800 and DP1000 dual-phase steels with average molybdenum contents of 0.18% and 0.33% respectively, resulting in a 4 kg weight saving.

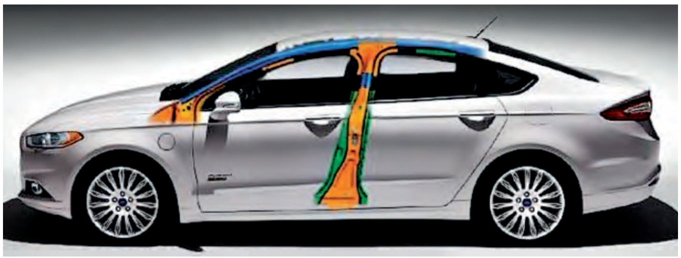


Figure 1: Ford Fusion with A-pillar/roof rail and B-pillars highlighted: The B-pillar plays a pivotal role in side-impact crash protection. © Ford

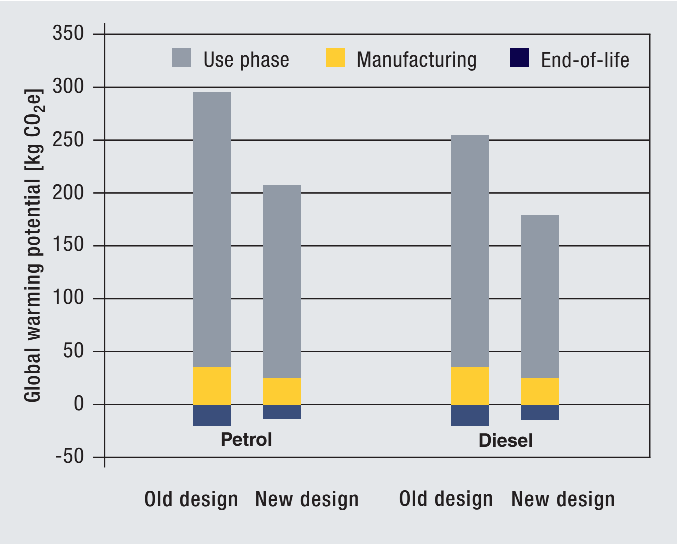


Figure 2: Life cycle GWP for one B-pillar. Results are shown for both diesel and petrol drivetrain.

Assessing the benefits

When assessing the relative environmental performance of the old and new B-pillar designs, it is important to take into account the complete life cycle of the part from production and manufacturing and its use in the vehicle through to its end-of-life.

Life Cycle Assessment (LCA), which measures total lifetime environmental impact, has been used to analyze the old and the new B-pillars. Four major life cycle stages were identified: Steelmaking and casting; rolling, finishing and forming; vehicle use; and end-of-life.

Data and assumptions

Data from a number of industry sources were used in the development of the LCA model. The new B-pillar comprises 76% DP800 and 24% DP1000 as estimated from technical drawings. The composition of the individual steel grades was determined from data provided by steel producers. Fuel consumption was estimated using Fuel Reduction Values (FRV) commonly used in the European automotive industry. The study assumed a lifetime vehicle mileage of 200,000 km.

The worldsteel dataset has been used to calculate the overall environmental benefits/burdens attributable to recycling at end-of-life. Background datasets related to alloys, materials and fuels were sourced from the GaBi database developed by PE International, now known as thinkstep.

ECOLOGY ECONOMY SOCIETY

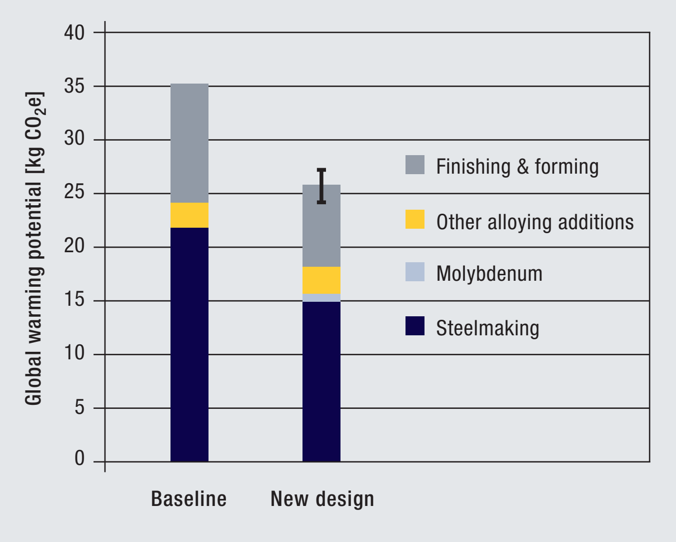


Figure 3: GWP for the manufacturing of the two B-pillar designs, with error bar to indicate uncertainty surrounding the hydroforming impact of the new design.

Environmental assessment results

Results generated for the full life cycle of the vehicle B-pillar indicate that the new design has a lower impact across all environmental metrics. **Figure 2** illustrates the results for global warming potential (GWP) for one B-pillar, showing a significant reduction in GWP between the old and new designs.

A credit at end-of-life related to steel recycling is shown in the graph as a negative value below the x-axis. This represents the reduced environmental burden in the next life cycle due to the reduced requirement for steel from virgin material.

Figure 3 illustrates the GWP due to manufacturing and shows the contribution made by molybdenum and other alloying elements. Similar results were obtained for all the other metrics assessed, with the new design having a lower impact in all cases. An error bar has been included in the graph to show the potential effect of a ±20% change in the impact of finishing and forming, as data for the impact of the hydroforming process had to be estimated.

Summary and conclusions

The assessment of the life cycle impact of selected environmental metrics relevant to the automotive sector indicates that the new hydroformed DP800/DP1000 B-pillar design has significantly lower impacts than the previous boron steel design.

The 4 kg weight reduction leads to considerable use phase savings, which drives the difference in impact between the two parts. The GWP saving for both B-pillars in the Ford Fusion over a 200,000 km total driving distance is 165 kg CO_2e for a petrol drivetrain and 141 kg CO_2e for a diesel drivetrain. This is equivalent to driving the vehicle over 1,000 km.

Looking solely at the impacts of manufacturing, the small increase in impacts due to the increased use of alloying elements including molybdenum is far outweighed by the savings in ironmaking and secondary steelmaking.

Crucially, these improvements have been achieved while actually improving the crash performance of the B-pillar, as illustrated in **figure 4**. Ford also estimates that the redesign has yielded a significant cost saving.

Overall the results of this study indicate that the switch to a DP800/DP1000 B-pillar design has yielded a benefit on an environmental, economic and a social level – in other words all three pillars of sustainable development. This demonstrates the potential improvements that can be achieved by using advanced high-strength steel grades with innovative manufacturing techniques, and the contribution that molybdenum can make in supporting similar innovations in the future.

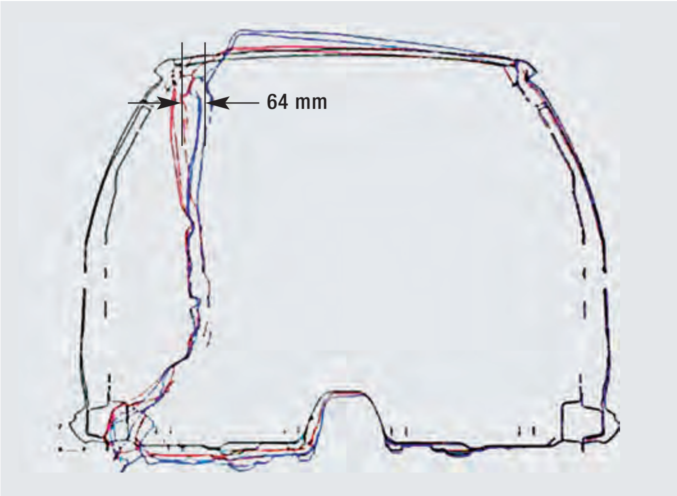


Figure 4: Crash performance of the Fusion B-Pillar: In a side impact, the new design (shown in red) has a lower intrusion at the top of the passenger compartment. © Ford

For further information, please see the full case study in the sustainability section of the IMOA website: http://www.imoa.info/download_files/sustainability/IMOA_Automotive-Case-Study.pdf

Low carbon power generation

Tackling climate change requires substantial and sustained reductions of greenhouse gases – approximately 25% of which arise from electricity generation. With energy demand forecast to grow by more than one-third in the next 25 years, low and carbon-free forms of electricity generation must play a bigger role in the future. Molybdenum already makes an important contribution to many renewable technologies.

Hydroelectric

Hydroelectric power is the most widely used renewable source, supplying some 16% of global electricity demand. High-strength steel (HSS) is used to manufacture penstocks (the very large diameter pipes delivering the headwater to the turbines) with thinner walls, permitting a larger internal diameter of pipe, which increases efficiency. Stronger steels use less raw material, need less welding and save energy in transport and construction. The addition of molybdenum to higher grades of HSS increases yield strength while maintaining toughness and hardenability.

The Itaipú hydroelectric plant on the borders of Brazil and Paraguay operates 20 penstocks, each having a 10.5 meter inner diameter and a weight of 883 tonnes. Each year, Itaipú generates close to 100 TWh of electricity, avoiding the emission of some 67 million tonnes of CO_2 compared with coal-fired generation.

Molybdenum-containing steels are often used in high-wear environments where frequent maintenance or replacement would be difficult, hazardous or costly

Wind

Global installed wind capacity reached 369 GW at the end of 2014, representing around 3% of global electricity generation. Wind is the most iron and steel-intensive of all power generation methods, with current designs using about 300 metric tonnes per installed MW of capacity.

Practically all the gears, bearings and shafts in most commercial wind turbine assemblies are constructed from molybdenum-alloyed engineering steels for hardness, durability and weight reduction. In a typical unit, the nacelle weighs up to 400 tonnes, supported at a height of 100 meters. With an expected increase in component size for improved performance, weight reduction continues to be an important issue and using molybdenum-alloyed thinner gauge steels in the housing and support frames could achieve weight reductions of 20 to 40%.

Wear resistance in the gears is also an important factor, especially as the units increase in size. Premature failure of the materials has been identified as a problem as more stress is placed on components in these large units. The use of case hardening steels containing molybdenum improves material performance and minimizes downtime and replacement costs, a significant factor in offshore installations.

Molybdenum plays an important role in next generation thin-film photovoltaic panels

Solar

On average, the earth's surface continuously receives more than 1,000 W/m^2 of solar energy, which can be converted into electricity. The proportion of total energy demand met from non-fossil sources has increased steadily since the late 20th century and is predicted to more than double by 2050, with the contribution met by solar energy increasing more rapidly.

Solar energy consumes only sunlight in generating electricity and is therefore considered a sustainable resource. Peak solar generation naturally coincides with some peaks of electrical demand, thereby reducing the overall requirement for baseload generation, which is often fossil fuel.

Compared to traditional rigid silicon panels, modern thin-film photovoltaic panels have advantages in manufacturing, cost and flexibility of design. Molybdenum plays an important role in these rapidly growing technologies, as one of the metals (or the only metal) in the back electrode of a thin-film panel.

Case study in brief

Thin-film photovoltaic solar panels

Modern thin-film photovoltaic (TFPV) panels are easier and cheaper to manufacture than traditional crystalline silicon arrays. Molybdenum is used in the back electrode of TFPV panels as it withstands the high temperatures used in manufacturing and the associated high temperature corrosion from other manufacturing materials.

Using molybdenum also helps to make the panels more efficient at converting sunshine into electricity. Panels using CIGS or CdTe as the absorber material also have some of the shortest energy payback times of all technologies, in the region of 0.9–1.5 years.

For further information, please see the full case study in the sustainability section of the IMOA website: http://www.imoa.info/download_files/sustainability/IMOA_solar_15.pdf

ECOLOGY ECONOMY SOCIETY

Protecting the environment

Emissions of sulfur dioxide (SO_2) from burning fossil fuels for electricity generation and transport have been identified as causing long-term damage to the environment through the formation of acid rain. Molybdenum plays a key role in technologies that are already protecting the environment against further damage from SO_2.

Flue Gas Desulfurization (FGD)

The most widely used FGD system for coal-fired power plants is the wet limestone-gypsum process in which sulfur dioxide and other acidic flue gases are neutralized by calcium carbonate. The chemical reaction produces a very aggressive environment inside the scrubber so a corrosion resistant material or a protective lining is used. Carbon steel absorber vessels lined with non-metallic materials were originally favored but failed very quickly. Modern systems are either built entirely out of molybdenum-containing stainless steel or carbon steel protected by a molybdenum-containing stainless steel lining with more corrosion resistant nickel-based alloy used at critical areas within the system.

Corrosion-resistant stainless steels and nickel-based alloys play a critical role in protecting the environment from acid rain

Fuel desulfurization

Sulfur compounds are removed from gasoline and diesel automotive fuel at the refinery to meet increasingly stringent emission limits and to prevent damage to vehicle catalytic converters, which further reduce environmental pollution. The process, known as catalytic hydrodesulfurization, removes sulfur by reaction with hydrogen and can be achieved with molybdenum-based catalysts. Their use has become more important with the increasing sulfur content of crude oil.

Case study in depth

Hydrodesulfurization of diesel fuel with molybdenum-based catalysts

The challenge

When diesel containing organically-bound sulfur is combusted, sulfur dioxide is released, causing acidification of the atmosphere and contributing to acid rain. It can also cause or aggravate respiratory problems. In addition, sulfur dioxide damages the catalytic convertors used to remove carbon monoxide, nitrogen oxides and hydrocarbons from vehicle exhausts.

The solution

Attempts to reduce sulfur in diesel fuel date back to the 1960s. By the late 1980s, sulfur content in diesel was typically 2000–3000 parts per million (ppm). The first EU directive regulating sulfur content in diesel fuel for passenger vehicles set the limit at 2000 ppm, known as Euro I, in 1993. Subsequent targets further reduced the limit, reaching today's 10 ppm (Euro V) level in 2009, requiring ultra-low sulfur diesel (ULSD).

How molybdenum can help

This rapid reduction in sulfur content was made possible by innovations in the hydrodesulfurization process. To remove sulfur it uses a molybdenum-based catalyst, which increases the rate at which hydrogen reacts with the organically-bound sulfur in the hydrocarbon feedstock during the refining process. After two years operation in a hydrodesulfurization plant, the catalyst is regenerated and thanks to this process, may be used for two further cycles before being recycled.

PE International, now known as thinkstep, used Life Cycle Assessment (LCA) to compare the impacts of combusting 2000 ppm Euro I diesel used in 1993 with the 10 ppm Euro V diesel used today and to quantify any additional impacts associated with increased sulfur removal.

Exhaust fumes from a passenger car. Cars are a significant source of emissions that cause smog and reduce air quality in urban areas.

Assessing the benefit

LCA was used to assess the total lifetime environmental impacts of the two fuels. Six life cycle stages were modeled in greater detail. These were: Diesel production from crude oil extraction to the desulfurization plant; catalyst production; hydrodesulfurization; catalyst regeneration; catalyst recycling at end-of-life; and diesel consumption in a passenger vehicle (use phase).

Six environmental impacts were assessed: acidification potential; global warming potential; smog creation potential; particulate matter/respiratory inorganics; eutrophication potential; and primary energy demand.

Data and assumptions

Catalyst production

Key data on the production of a cobalt-molybdenum catalyst was provided by Haldor Topsøe, a market leader in the manufacture of industrial catalysts. Primary data for 2013 was used for modeling the production of catalysts in both 1993 and 2013. Upstream datasets related to alloys, materials and fuels were sourced from the GaBi database developed and maintained by PE International.

Hydrodesulfurization

Improvements in catalysts and plant efficiency have offset any increase in energy consumption (due to increased sulfur removal) between 1993 and 2013. It was therefore assumed that the energy consumption in the plant was the same for producing both fuels. Other refinery processes relating to the production of diesel were also modeled as being unaltered.

Regeneration and recycling

Regeneration of the catalyst was modeled based on information from the catalyst manufacturer. The catalyst completes about two and a half, two-year cycles with a regeneration treatment carried out after each cycle. Credits for the avoided production of primary molybdenum trioxide, cobalt and nickel due to recycling were applied.

Use phase

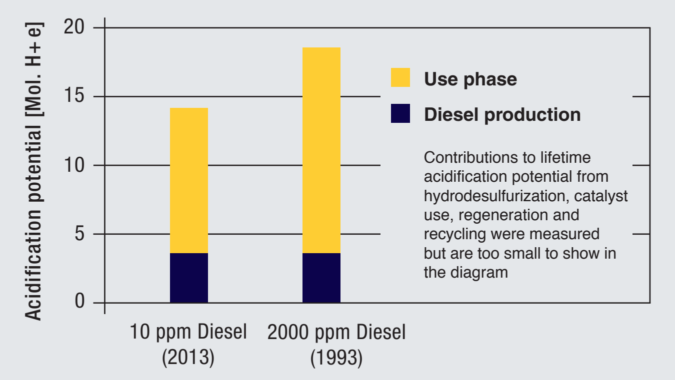
The emissions profile of diesel vehicles has improved significantly in the past two decades. An average mid-sized Euro V diesel passenger car has been used for comparison in both scenarios to avoid the effect of improvements in vehicle performance rather than fuel.

Environmental assessment results

Results for the full life cycle show that ULSD has a lower impact than the 2000 ppm fuel in acidification, smog creation potential and particulate matter/respiratory inorganics. For the other three impact categories, there is effectively no change, as emissions of sulfur dioxide do not contribute to these categories.

Acidification potential

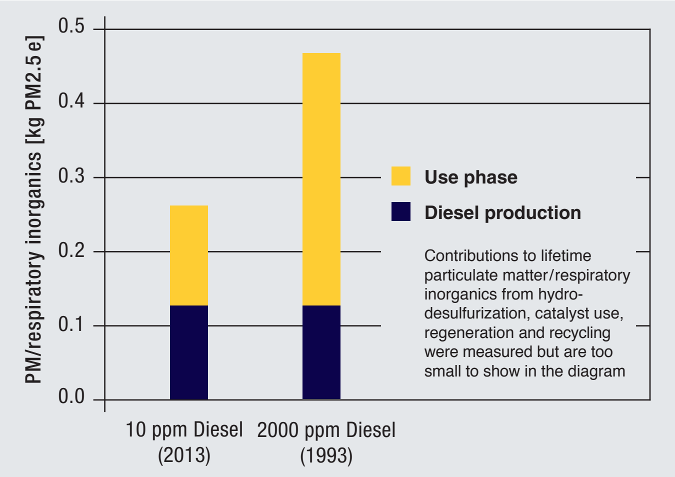
The 10 ppm diesel shows a reduction in acidification potential of 24%. Hydrodesulfurization contributes only 0.3% of the overall impact, with the catalyst accounting for only 0.06% of the overall acidification impact.



Lifetime acidification impact for 10 ppm and 2000 ppm diesel

Particulate matter/respiratory inorganics

The impact from 10 ppm diesel on particulate matter (PM) was 44% lower than the impact from 2000 ppm diesel. This category is dominated by the impact of the use phase and diesel production processes other than hydrodesulfurization.



Lifetime particulate matter/respiratory inorganics impact for 10 ppm and 2000 ppm diesel

Global warming potential (GWP)

In terms of GWP, almost no difference is observed in the impacts of the two fuel types. The hydrodesulfurization process contributes 0.7% to the total, of which only 0.005% is attributable to the catalyst.

Discussion and sensitivity

To test the sensitivity of the results, fuel and electricity consumption for the desulfurization process were doubled, resulting in impacts increasing from between 0.03% to 0.8% – all significantly lower than the reductions in impacts from low sulfur diesel use.

It was also important to note that the emissions profile of diesel vehicles has improved significantly in the past two decades. A comparison of Euro I and Euro V vehicles over a set 200,000 km lifetime shows improvements in GWP, eutrophication and primary energy demand of at least 17%, improvements in acidification of 75% and a ten-fold reduction in impacts from particulate matter/respiratory inorganics. A mid-sized Euro V diesel passenger car was used for comparison in both scenarios to avoid the effect of vehicle improvements on the results.

ULSD has been criticized for reducing fuel efficiency by 1–2%, but an EU analysis found 2–3% increases in fuel economy in new vehicle models when moving from 50 to 10 ppm diesel. This and other secondary benefits such as the associated reduction in CO/NOx emissions have been omitted from this study.

Summary and conclusions

Hydrodesulfurization of diesel fuel has been extremely effective in reducing SO_2 emissions from road vehicles. The use of 10 ppm diesel represents an annual reduction of 754,000 tonnes, or 287 million m^3 of sulfur dioxide emissions, based on 2011 demand in the EU. Sulfur dioxide emissions from this sector are now at least 100 times lower than they were in 1993, despite a doubling in diesel demand in the past 20 years.

Importantly, the additional catalyst and its regeneration required to create 10 ppm diesel does not meaningfully increase any of the LCA metrics. Overall, impacts from hydrodesulfurization represent less than 1% of the total impact for all categories.

From a social perspective, air quality has improved dramatically in cities, and sensitive natural environments are more protected from damage by acid rain. A study by the US Environmental Protection Agency found that reducing sulfur in fuel led to a significant reduction in respiratory problems linked to premature death. Another benefit is the reduced damage to historic buildings in cities, many of which were badly affected by acid rain in the last decades of the 20th century.

Overall, the results demonstrate the important environmental benefits gained over the last twenty years with sulfur removal through hydrodesulfurization, made possible by molybdenum-containing catalysts.

For further information, please see the full case study in the sustainability section of the IMOA website: http://www.imoa.info/download_files/sustainability/IMOA_Hydrodesulfurization-Case-Study.pdf

Conserving resources

Safeguarding the supply of raw materials through resource conservation is essential to a more sustainable future. Molybdenum strengthens steel, reducing the quantity needed for certain applications. In stainless steel, molybdenum enhances corrosion resistance, increasing the service life of products, components and structures.

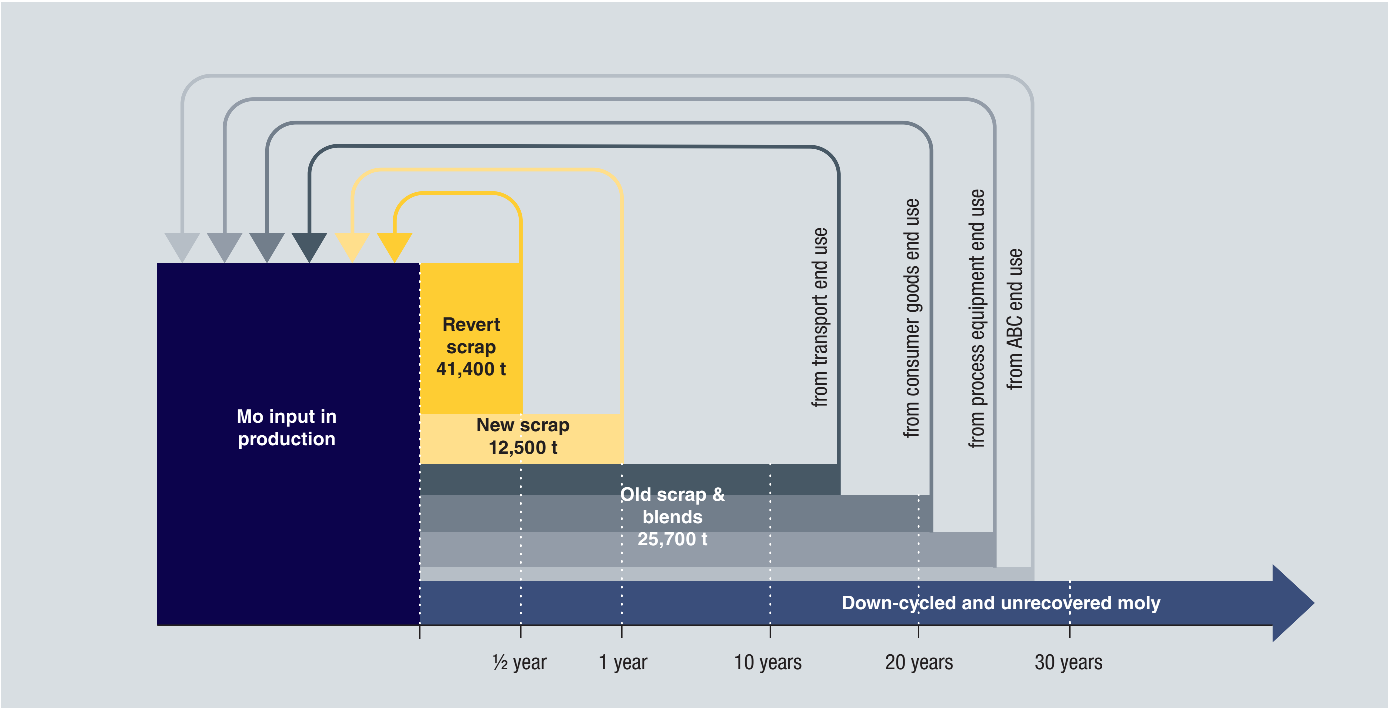
Construction

Stainless steel, already a very durable architectural material, becomes much more resistant to corrosion caused by chlorides (from coastal or deicing salts) and pollution with the addition of molybdenum. This makes properly selected molybdenum-containing stainless steels the ideal choice for buildings, bridges, transit facilities, urban furniture, sculptures and many other applications.

In large projects such as bridges and stadia, high-strength steel (HSS) enables stronger and lighter structures than conventional steel, saving resources as well as cost and energy in transportation and fabrication. Parts of the roof of the Friends Arena in Stockholm, Sweden, were constructed with HSS, reducing total steel usage by 17% and total costs by 14.5%, generating a 17% reduction in greenhouse gas emissions compared to conventional steel over the life cycle of the stadium.

The Millau Viaduct in France is another example, comprising seven piers of reinforced concrete topped with HSS pylons, saving 80,000 tonnes of steel and reinforced concrete which would otherwise have been required using conventional steel. Further weight savings of about 18,000 tonnes were made using molybdenum-bearing HSS in the road deck.

Molybdenum-containing high-strength steels reduce weight in construction projects, saving raw materials, cost and energy.



The molybdenum scrap reuse cycle for 2011. Of the 25% total scrap input, 13% was revert scrap and 4% each new scrap, old scrap and blends. (SMR.2012)

Recycling

Stainless steel is 100% recyclable with no loss in quality or down-cycling, regardless of how many times it is recycled. The typical recycled content of all stainless steels is about 60%, rising to 75–85% in stainless steels produced in North America. Globally, nearly 80% of all stainless steel is recycled at its end-of-life. Researchers in the US and Japan have estimated that 92% of stainless steel used in the building and infrastructure sector is recycled.

Molybdenum is readily recycled as well. Of the 330,000 tonnes of molybdenum used in all applications worldwide in 2013, some 86,000 tonnes, or 26%, came from recycled sources. In the same year, the share of recycled molybdenum used in stainless steel production was 39%, rising to 50% in tool and high speed steels.

Case study in depth
Myllysilta bridge

The challenge

The Myllysilta bridge is a road crossing of the Aurajoki River in the coastal city of Turku in Finland. Following the structural failure of a previous bridge in 2010, a design bid was issued for its replacement and the construction of the new bridge was completed in November 2011.

The Aurajoki is a brackish river and deicing salts are extensively used on the road surface throughout the long winter months. Therefore, the cladding of the new bridge had to be highly corrosion resistant. It was also essential that the material chosen required minimal maintenance.

The solution

Stainless steel was specified as the cladding material for the underside of the bridge for a combination of life cycle cost savings, aesthetics and practical reasons. Duplex stainless steel grade 2205 (EN 1.4462 or S32205), containing 3.1% molybdenum, was chosen as it is readily available, cost-effective and highly durable in such an aggressive environment.

How molybdenum can help

Molybdenum improves the corrosion resistance of all stainless steels. It has a particularly strong effect on pitting and crevice corrosion resistance, for example in harsh coastal environments and where deicing salts are present.

Assessing the benefit

A Life Cycle Assessment (LCA) conducted by WSP examined the relative environmental impacts of duplex stainless steel compared with a possible alternative of mild steel treated with a zinc-epoxy paint to protect against corrosion.

The Myllysilta (literally meaning: 'Mill Bridge') is a road crossing of the Aurajoki River in the coastal city of Turku in Finland.

The LCA focused on aspects of the life cycle of the cladding that differ between the two steel solutions and their associated surface treatment, including any maintenance and replacement required within the 100-year design life. It also included the impacts and benefits related to recycling the cladding material at its end-of-life.

The LCA compared the impacts of the two materials and any potential trade-offs between life cycle phases. It considered the relevant categories of environmental impact, including the contribution to global warming, acidification, eutrophication, photochemical ozone creation and the consumption of non-renewable energy sources.

Data and assumptions

The study avoided comparing the aspects of the life cycle inventory which were not significantly different for the two options, such as cutting and shaping of the cladding, initial delivery and installation of the original cladding, and its removal at the end of the 100-year design life.

Impacts of manufacturing steel

Data for the impacts of manufacturing the required 82 tonnes of cold-rolled stainless steel sheet (grade 2205) was provided by Outokumpu, the manufacturer of the stainless steel used to clad the bridge. This was based on their European plants which use electric arc furnaces and an average 61% scrap stainless steel content.

Data for the same quantity of cold-rolled mild steel sheet was provided by the World Steel Association, based on average production across the European Union. This included the use of blast furnaces fed by an average of 0.11 kg of ferrous scrap and 1.36 kg of iron ore for each 1 kg of steel produced (i.e. 11% scrap content).

Impacts of manufacturing anti-corrosion paint

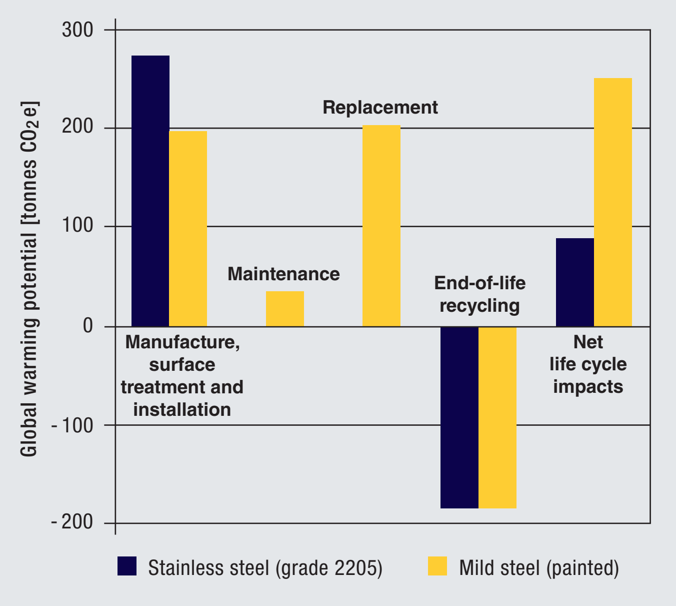
For the mild steel cladding option, it was assumed that a three-layer zinc-epoxy paint system (Tiel 4.20) would be required to provide appropriate corrosion resistance, in line with the standards for bridges in Finland.

Impacts of surface treatment

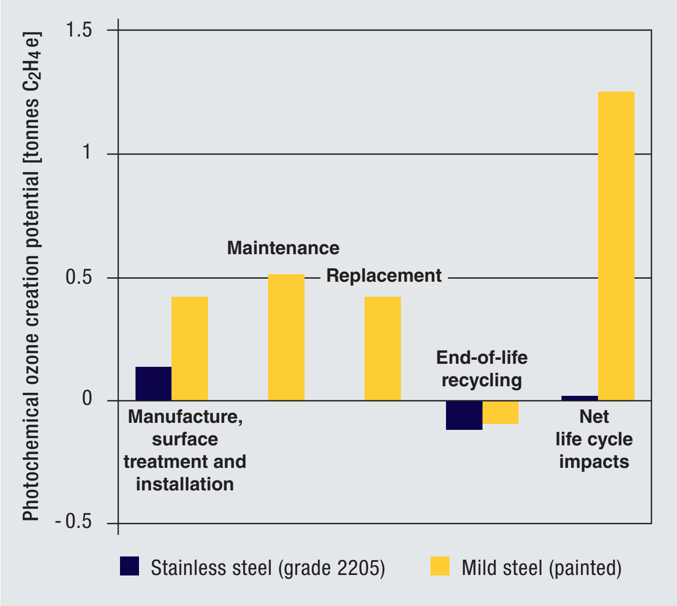
For the stainless steel cladding option, the impacts of energy associated with the brushed surface finish were included. For the mild steel option, the impacts of preparing and painting the steel sheet were assessed, based upon published specifications for anti-corrosion paint. Energy consumption impact was based on Finnish grid electricity.

Impacts of maintenance

For the mild steel option, it was assumed that the anti-corrosion paint would have to be removed and reapplied every 20 years, based upon paint specification and industry experience.



Global warming potential of stainless steel and mild steel options



Photochemical ozone creation potential of stainless steel and mild steel options

Impacts of replacement of cladding
Stripping and repainting would still result in gradual deterioration of the steel cladding due to edge corrosion and pitting, therefore it was assumed that the cladding would be replaced after it had been repainted twice (after 60 years).

Impacts of end-of-life recycling
The environmental impacts of end-of-life recycling of stainless steel and mild steel were provided by the stainless steel producer and the World Steel Association respectively. In Europe, 95% of these steels are recycled at end-of-life, reducing the demand for virgin resources, thus the environmental impact is actually negative (i.e. environmental impacts are avoided). In the case of stainless steel, this 'recycling credit' is highly significant, approaching (and for one of the metrics exceeding) the original manufacturing impact. This is due to the low environmental impacts for this producer in comparison to the recycling credit, which is based upon European averages. The original and replacement mild steel cladding also achieves a 'recycling credit' although this is not as significant as that for stainless steel.

Life cycle assessment summary and conclusions

A Life Cycle Assessment (LCA) was completed for the comparative environmental impacts of the use of 2205 duplex stainless steel and mild steel cladding for the Myllysilta Bridge in Finland. The results indicate that stainless steel ***presents significant net benefits across all major impact categories***. The use of stainless steel rather than painted mild steel saves:

- Around 65% of the global warming potential
- Around 66% of the eutrophication potential
- Around 99% of the photochemical ozone creation potential
- Around 37% of the primary energy demand (non-renewable)

Molybdenum-containing stainless steel (grade 2205) therefore offers significant life cycle environmental benefits in the case of the Myllysilta bridge and avoids the cost, complexity and safety issues of lifetime maintenance in this or other equally harsh environments.

A sensitivity test was performed using European average data (rather than data from the cladding manufacturer) for the life cycle impacts of manufacturing stainless steel (2205). Net life cycle impacts were still lower than those for the mild steel option for all but acidification potential. This may be due to a lower proportion of renewable energy in the mix compared to the manufacturer's data.

For further information, please see the full case study in the sustainability section of the IMOA website: http://www.imoa.info/download_files/sustainability/IMOA_Myllysilta-Bridge-Case-Study.pdf

Quality of life

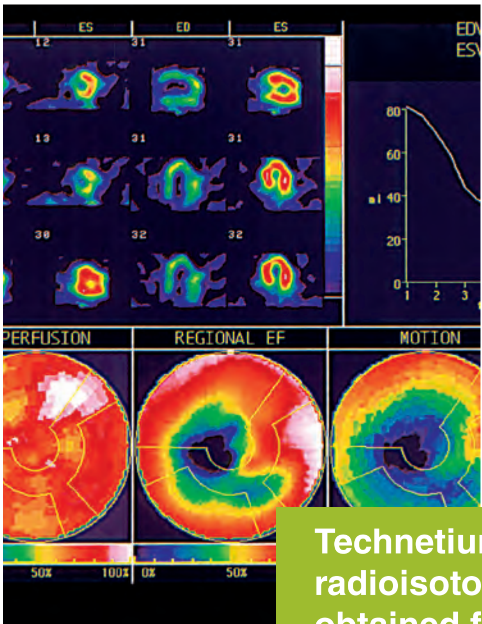
Molybdenum touches our everyday lives in many ways, from the very ordinary and mundane to the truly extraordinary and life-saving. With a key role in technologies that support life, molybdenum contributes to sustainable development in some surprising applications.

Medical imaging

Molybdenum-99 (Mo-99), an isotope of molybdenum, decays directly into technetium-99m (99mTc) and is the only source of this radioisotope, used in some 85% of all nuclear medical diagnostic procedures.

99mTc has a half-life of six hours, long enough for diagnostic purposes but short enough to minimize the radiation dose to the patient. It produces low energy gamma rays, enabling organs and any abnormalities to be visualized with lower doses of radiation.

It provides a non-invasive means of quickly determining the condition of the heart and other organs, thereby avoiding unnecessary surgery. Imaging has also transformed the management and treatment of breast, skin and other cancers by visualizing their location and shape clearly, enabling such precise targeting that minimally invasive procedures have replaced major surgery in many cases.



Technetium-99m is the most extensively used radioisotope for diagnostic imaging and can only be obtained from molybdenum

Agriculture

Molybdenum is an important plant micronutrient, and is essential for the production of enzymes which enable nitrogen to be obtained from air and water. Without it, plants suffer from poor growth, leaves may become pale and deformed and buds and flowers may not develop properly.

Acidic soils can prevent uptake of molybdenum and this can usually be corrected by applying lime. However, some soils do not have enough molybdenum and correcting the deficiency with appropriate fertilizer, seed or foliar treatments can increase crop yield by as much as 60%. Correcting molybdenum deficiency also helps to ensure more efficient and cost-effective use of nitrogen fertilizer.

Global food demand is predicted to double in the next 50 years and optimizing output from existing capacity will help to preserve biodiversity by minimizing the amount of additional land turned over to food production.

Case study in brief

Plant micronutrients

ECOLOGY ECONOMY SOCIETY

Molybdenum is essential for healthy plant life, playing a key role in ‘fixing’ nitrogen from air and water, necessary for the production of amino acids, proteins and chlorophyll. Soils in some regions of the world are naturally low in molybdenum. This can also occur in peat soils and in highly-weathered soils low in nutrients. Molybdenum deficiency is often revealed by poor yields and is the most widespread nutrient deficiency in soil after zinc and boron. It is estimated that nearly half of all agricultural soils in China are deficient.

Correcting molybdenum deficiency where it exists can produce dramatic results. Studies in Australia have demonstrated increases in grain yield by as much as 60% following correction. Fertilizers are an ideal method of delivering molybdenum and other nutrients; farmers can also treat the crop seed or apply specially formulated foliar sprays. A study in Egypt recorded increases in yield of nearly 40% from mandarin trees treated with a molybdenum foliar spray.

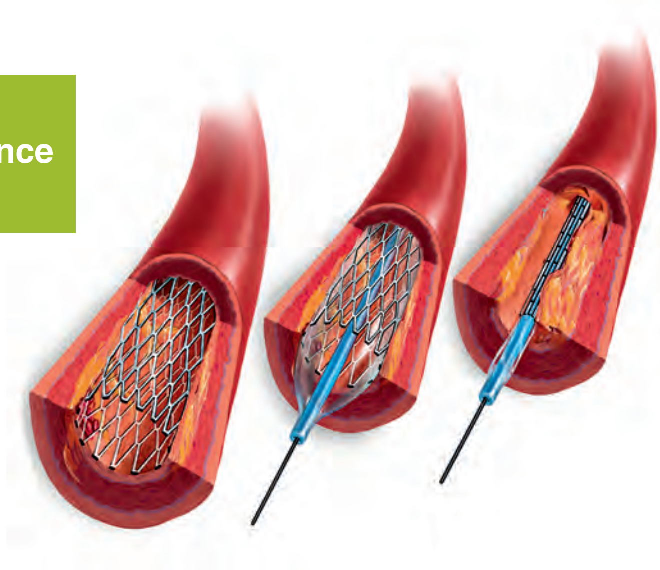
For further information, please see the full case study in the sustainability section of the IMOA website: http://www.imoa.info/download_files/sustainability/IMOA_Micronutrient.pdf

Stents

Coronary heart disease is the number one cause of deaths worldwide. Blockages in arteries reduce oxygen supply and often result in a heart attack. Angioplasty uses a catheterized balloon which is inflated to re-open the artery. A coronary stent, a tubular section of stainless steel mesh inserted into the artery to keep it open permanently, was first demonstrated in 1986. Stents are manufactured from molybdenum-containing stainless steel as they need to be strong and resistant to corrosion.

Angioplasty with stent intervention was 75% more successful than angioplasty alone within a few years of its introduction. The success rate has been further increased in recent years with thinner, more flexible stents which are easier to guide into place and less likely to damage the artery. These new stents contain up to 10% molybdenum and can be made smaller, allowing their placement into thinner arteries, further reducing the likelihood of a blockage reoccurring.

Molybdenum-bearing alloys have been used to manufacture stents since their invention in the 1980s



Desalination plants

Currently some three billion people – about 40% of the global population – live in water-scarce regions, with more than three-quarters of a billion, or approximately one in ten, without access to safe water. By 2025, it is estimated that 1.8 billion people will be living in countries or regions with absolute water scarcity. Desalination is an established technology for delivering fresh water in arid areas. In use for many decades, it has grown rapidly in response to population growth, industrialization and higher living standards.

However, the high salinity and high temperatures in thermal distillation plants, and high pressures in reverse osmosis plants, produce extremely corrosive operating environments. Using molybdenum-containing stainless steel protects these strategic assets from the inherent problem of corrosion, which would otherwise render them unviable due to the frequency and prohibitive cost of refurbishment and replacement.

Case study in brief

Desalination plants

Some 17,000 desalination plants around the world supply 81 million cubic meters of fresh water every day.

Desalination plants work using distillation or reverse osmosis and the combination of salinity and high temperature or pressure produces a very corrosive environment. Early examples of plants constructed from mild steel have long since been replaced with corrosion-resistant steels alloyed with molybdenum.

Modern thermal distillation plants are now constructed using molybdenum-containing duplex stainless steels while 6% molybdenum steel is often specified for reverse osmosis plants.

Molybdenum plays a vital role in safeguarding the operation of these plants, without which they would very quickly require replacement.

For further information, please see the full case study in the sustainability section of the IMOA website: http://www.imoa.info/download_files/sustainability/IMOA_Desalination.pdf

ECOLOGY ECONOMY SOCIETY

IMOA®

INTERNATIONAL MOLYBDENUM ASSOCIATION
THE VOICE OF THE MOLYBDENUM INDUSTRY

ISBN 978-1-907470-35-6

www.imoa.info