

RQ CLEAN ENERGY sizing up the *real* **carbon** **footprint**

Carbon dioxide has for several years sat alongside noxious exhaust products within the scope of emissions regulations worldwide. But now, if we wish to progress to a reliable and holistic measure of sustainability, is it time to ask whether we are measuring the correct things and measuring them correctly, too? **Anthony Smith** reports on the latest thinking in life cycle carbon dioxide assessment

The environmental performance stickers on the windscreens of new cars in showrooms across Europe these days are pretty clear in stating precisely the carbon emissions for each product. Potential purchasers are quickly and clearly informed about the CO₂ emissions per kilometre driven, and are incentivised by the many national, state and even city tax breaks and waivers on parking fees and tolls, such as London's congestion charge.

The carbon emissions of vehicles have even entered everyday conversation in the same way that fuel-economy and performance did in previous years: drivers are readily able to quote the official carbon dioxide emissions of their cherished new cars well ahead of other performance details.

But how reliable are these ubiquitous

'g/km CO₂' figures in assessing the true carbon footprint of each product throughout its life? In short, are we measuring the right things and making reliable comparisons – especially when evaluating alternative vehicle and powertrain types?

The current European metric for comparing the greenhouse gas emissions of passenger cars is the tailpipe CO₂ emissions per kilometre, measured over the New European Drive Cycle (NEDC) which is comprised of four phases of urban driving and one of extra-urban. The homologation test is carried out using a reference fuel on a dynamometer in a controlled laboratory environment. A cold start is followed by operation at an ambient temperature that must be within the range 20–30 degrees Celsius.

The EU is in the process of implementing fleet-averaged tailpipe CO₂ regulations based on these NEDC figures: these are critical as both non-compliance penalties and super-credits are applied to manufacturers with the aim of achieving an industry fleet average of 130 g CO₂/km by 2015 and, together with other measures, 95 g CO₂/km by 2020.

From test bed to real world

Given the rather abstract nature of any drive cycle, how reliable are the official NEDC figures as a measure of carbon emissions? Some insight into this is provided by the magazine *Autocar*, whose experienced test drivers regularly assess new cars for the benefit of the publication's readers, recording their own measurements of fuel consumption alongside the data published by the

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manufacturer.

A simple calculation can yield an equivalent figure for CO₂ emissions, showing that 'real-world' emissions during the vehicle tests range from 5 percent to 36 percent higher than the certified figures, with typical vehicles posting CO₂ emissions of around 20 percent higher. This discrepancy is also the case for two electric vehicles recently tested, where electrical energy consumption figures, expressed in terms of Wh/km, were similarly 15 percent and 54 percent higher.

While motoring journalists may, in some cases, have an arguably well-deserved reputation for aggressive driving, the wide range of these data clearly demonstrates that certification figures merely provide an approximate indication of real-world CO₂ emissions.

Life cycle analysis

If tailpipe emissions can be somewhat misleading in terms of real-world performance within themselves, they also clearly fail to fully represent the true carbon impact of a new product on its environment.

A vehicle's life cycle can be conveniently subdivided into four 'blocks', yet the current tailpipe emissions serve only to focus on one – the use of the vehicle. The three remaining 'blocks' crucial to an understanding of true life cycle impact are:

- the fuel chain that delivers the liquid fuel to the filling station forecourt or electric power to the charging socket for a plug-in vehicle;
- the end of life disposal and recycling of the vehicle and its components, and;
- the manufacturing supply chain of the vehicle.

This form of holistic analytical approach is already the basis of Environmental Product Declarations (EPDs) that are voluntarily applied to a range of consumer goods, such as clothing, in order to educate and reassure purchasers of the environmental provenance of the product. The carbon dioxide released into the atmosphere throughout the entire value chain that has delivered the product to its point of sale is expressed in mass terms, including the contributions of all relevant aspects of manufacture, logistics and marketing.

Carbon dioxide equivalence

While carbon dioxide emissions are thought of as one of the main contributors to climate change, CO₂ is far from being the only so-called

The four 'blocks' of a vehicle's life-cycle

The fuel chain



Manufacturing



Vehicle use



End of life recycling



A vehicle's life cycle can be conveniently subdivided into four 'blocks' of carbon emissions – the fuel chain, manufacturing, end of life recycling and use on the road – and yet current g/km carbon dioxide emissions regulations focus only on the last of these.

the frameworks provided by these standards as significant effort and subjective judgement are required in the identification and quantification of the many sources of greenhouse gas emissions. As a result, it is perfectly possible to conduct two LCAs of the same product with both analyses conforming to the ISO 14040 standards but delivering very different results.

Different fuel chains

In considering the LCA requirements of low-carbon vehicles, there are clear differences in the fuel chains that deliver liquid fuel and electric energy to the vehicle. But the position is further complicated – and made all the more urgent – by the widely differing manufacturing and production processes used – for battery electric and hybrid vehicles, for example – and the fact that many of these processes and the raw materials on which they are based are inherently carbon intensive.

Reliable and directly comparable

measures are thus necessary not just to inform decisions over vehicle choice – of both individual purchasers and large fleet operators – but also to direct future technological research towards addressing the most carbon-intensive aspects of low-carbon vehicle manufacture. Without such a measure, short-term economics alone is likely to be the primary driver of future research, and this may serve in part to limit any moves towards truly sustainable transport.

Life cycle assessment research

As part of an effort to inform the debate on vehicle life cycle carbon dioxide assessment, Ricardo prepared a report for the UK Low Carbon Vehicle Partnership, which was published in June 2011. Entitled *Preparing for a Life cycle CO₂ Measure*, the work sought to establish the viability of assessing a vehicle's life cycle carbon dioxide equivalent footprint.

The report highlights the increasing

'This work dispels the myth that low-carbon vehicles simply displace emissions from the exhaust to other sources'

Greg Archer, LowCVP managing director

importance of accounting for whole-life carbon emissions in the task of comparing the greenhouse gas emissions of low-carbon vehicles. It was prepared by Ricardo in collaboration with the expert membership of the Low Carbon Vehicle Partnership [LowCVP], which included major vehicle manufacturers and oil companies.

"This work dispels the myth that low-carbon vehicles simply displace emissions from the exhaust to other sources," explains LowCVP managing director Greg Archer. "However, it does also highlight the need to look at reducing carbon emissions from vehicles throughout their life cycle. The automotive industry is already taking positive steps to address this issue – the recent announcement by Toyota of a solar array to provide electricity to power the hybrid Auris production facility and wind power at the Nissan Leaf plant are excellent examples of this."

The study found that some of the CO₂ savings made during the use of low-carbon vehicles is offset by increased emissions created during their production and, to a lesser extent, their disposal. Yet, overall, electric and hybrid vehicles do still have lower carbon footprints than conventional fossil-fuelled cars. For example, a typical medium-sized family car will create around 24 tonnes of CO₂e during its life cycle, while an electric vehicle will produce around 18 tonnes over its life. For a battery electric vehicle, 46 percent of its total life cycle carbon footprint is generated at the factory, before it has travelled a single mile – so there is inevitably a trade-off in both time and distance travelled before a battery electric vehicle has a lower carbon emission than its conventionally powered equivalent.

Embedded carbon

For a standard mid-sized gasoline internal combustion engine vehicle the report shows that the embedded carbon in production will be around 5.6t CO₂e, the majority of which results from the

non-powertrain components (vehicle glider). This highlights the importance of applying vehicle light-weighting technologies to both the vehicle structure and interior, using materials that also have low embedded CO₂e emissions. A similar electric vehicle will have embedded production emissions of 8.8t CO₂e, 43 percent of which arise from the battery pack. Decarbonizing both the electricity supply through the use of renewable sources of power – as well as the production of batteries – will therefore be essential for electric vehicles to deliver ultra-low carbon lifetime emissions.

The report also indicates that life cycle carbon emissions for future mid-sized petrol and diesel vehicles doing an equivalent lifetime mileage could be very similar, as continuing progress is made towards reducing the tailpipe emissions of these conventional technologies. It reveals too that some regulations designed to improve recyclability, safety or to reduce air pollution can increase carbon emissions in production or use.

Towards a reliable and repeatable standard

The Ricardo report for LowCVP clearly highlights the need for a more all-embracing and consistent standard for life cycle carbon dioxide assessment, as Ricardo chief innovation and technology officer Neville Jackson observes: "There

is an emerging consensus that we need to move towards a more holistic analysis of whole-life CO₂ emissions in order to make more informed and better long-term decisions on future technologies."

In years to come, as a wider range of electric, biofuel and potentially hydrogen vehicles begin to compete with petrol and diesel models, it will become essential to compare vehicles on a whole-life carbon basis. The study shows not just the complexity but also the practicalities of calculating whole-life carbon emissions and highlights the need to develop a standard methodology acceptable to vehicle manufacturers.

"Life cycle analysis is still in its infancy, with little defined process and standards," continues Jackson. "This report is an important contribution to this type of analysis and highlights the need to work towards a common methodology and approach in order to deliver consistent and robust life cycle data on CO₂ emissions."

This is a viewpoint clearly shared by Greg Archer: "We already measure the whole-life carbon emissions of biofuels, and doing the same for vehicles is entirely feasible. However, it does now require effort to be directed at agreeing how this should be done consistently at an EU, or possibly global, level."

The report highlights the need to decarbonize both the electricity supply and the production of batteries for electric vehicles to deliver ultra-low life cycle carbon emissions.



Case Study: Balancing cash & corporate social responsibility



Taking the concepts of life cycle carbon dioxide assessment as set-out in the previous article, the following study was reported by Ricardo at the Cenex Low Carbon Vehicles 2011 event held at Rockingham, UK, in September

In addressing sometimes aggressive targets for reducing corporate CO₂ footprints, fleet operators face some stark choices in the replacement and upgrading of vehicles. Low-carbon technologies are almost always more expensive to acquire, but they typically yield savings in operating costs due to their lower overall fuel consumption and/or the substitution of fossil fuel with less expensive mains electricity supplies. However, as the previous article has shown, life cycle assessment studies show that full battery electric vehicles and hybrids carry higher embedded carbon emissions arising from their manufacture than do conventional vehicles. So will low-carbon vehicles really help reduce the corporate CO₂ footprint and can they do so while meeting the commercial needs of the organization?

The above questions were addressed in a case study presented by Ricardo at the Low Carbon Vehicles 2011 event. To introduce the concept of a carbon payback period, and how this would

UK supermarket chain Sainsbury's publicizes the launch of its first electric delivery vehicle (above), similar to the London based delivery operation described in Scenario B (right).

vary by circumstance, two contrasting scenarios were put forward. "The optimal choice of low-carbon vehicle will depend heavily both upon organizational objectives and on the intended duty cycle," explains Jane Patterson of the Ricardo advanced technology group. "To illustrate how this can influence the choice of low-carbon vehicle technologies we assessed the choices that would face a regional UK courier service operating a fleet of vehicles from a central depot averaging daily around 200 km each, and a central London supermarket operating delivery vehicles within a radius of 10km of the store on individual trips of around two hours."

Technology options

Three generic vehicle powertrain architecture options were considered as summarised in the chart (below/ left), each of which would provide a viable vehicle choice for each of the two scenarios. The first option was based upon

a conventional 2.1L four cylinder diesel powertrain with tailpipe CO₂ emissions of 222 g/km, while the second was based on an identical engine but within a full hybrid powertrain architecture delivering 167 g/km. The final option was a battery electric vehicle providing a comparable package and performance.

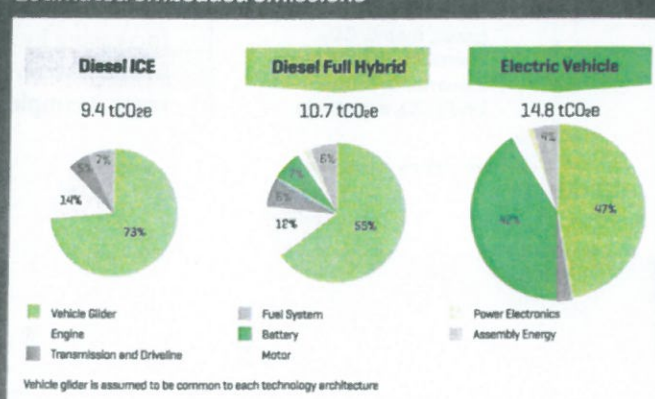
In practice there would be as many such options as there are candidate vehicle models available, but the focus on just three generic vehicles helps to simplify the analysis and demonstrate the life cycle based selection process that might be followed by a fleet manager.

The embedded carbon breakdown for these three generic vehicles is shown below, with the baseline diesel representing emissions of 9.4 tonnes CO₂e. The hybrid and battery electric vehicles represent embedded emissions that are respectively 14 percent and 57 percent higher, an increase largely attributable to the capacity of the battery in each case.

Generic vehicle architectures considered

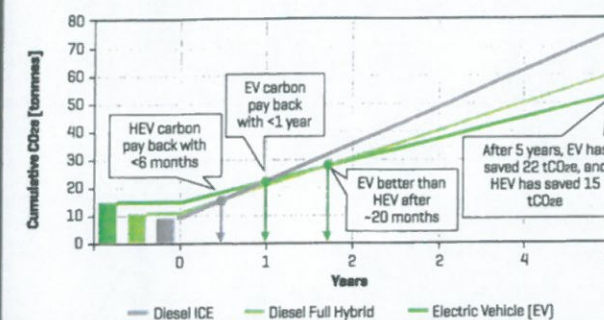
Vehicle Architecture	Kerb Weight	Fuel Consumption	Tailpipe CO ₂	Retail Price
Diesel ICE 2.1L 14 Diesel engine, 95kW	2410 kg	8.4 L/100km	222gCO ₂ /km	£25,000
Diesel Full Hybrid (HEV) 2.1L 14 Diesel engine, 3 kWh NiMH battery pack, 60 kW Motor	2560 kg	6.3 L/100km	167 gCO ₂ /km	£30,000
Electric Vehicle (EV) 45 kWh Li-ion battery, 120 kW Motor	2760 kg	0 gCO ₂ /km	0 gCO ₂ /km	£60,000

Estimated embedded emissions

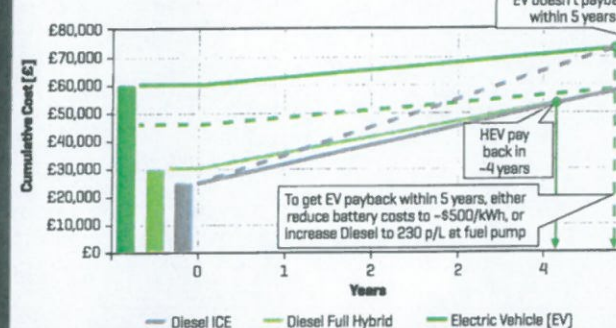


Scenario A – Regional courier service

Scenario A: Carbon Payback



Scenario A: Financial Payback



Scenario A: Courier service

Within this scenario based on a regional parcel distribution service, the initial embedded carbon of the hybrid vehicle is 'paid back' in the form of reduced tailpipe emissions after less than six months. Using the current UK government estimate of grid electricity carbon intensity (594 gCO₂e/kWh at the charge point), the battery electric vehicle similarly pays back its embedded carbon in less than a year. After five years the hybrid and battery electric powertrains save respectively 15 and 22 tonnes of CO₂e in comparison with the baseline diesel vehicle; the EV exceeding the hybrid in cumulative emissions savings after around 20 months.

However, if the carbon savings for the parcel delivery service in selecting the two low carbon vehicle options are attractive, the financial position is very different. While a financial payback in comparison with the baseline diesel is projected for the hybrid vehicle after just over four years, it may be nine years before the electric vehicle provides a positive return.

To assess the sensitivity to possible changing factors within this time horizon, the analysis was repeated assuming that the cost of the electric vehicle's Li-ion battery would reduce from current estimate of \$1000/kWh to the

\$500/kWh typical of NiMH cells. In such circumstances the financial payback results show that the EV would just break even within five years. Alternatively if fuel costs are increased from 140p to 230p/litre, the break-even position for the EV would be just within five years – or less than three years if both changes were to occur simultaneously.

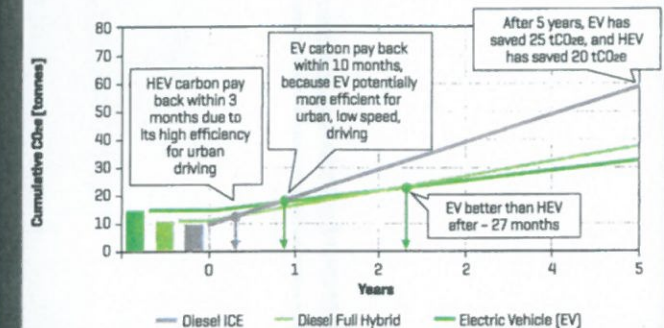
Scenario B: City based supermarket delivery service

Given the duty cycle of a local delivery service, the carbon payback is seen to occur within a year both for the hybrid and the electric vehicle; specifically, within three and ten months respectively. Moreover the EV is seen to perform better in terms of cumulative emissions than the hybrid after 27 months, achieving total savings of 25 tonnes CO₂e over five years in comparison 20 tonnes for the hybrid.

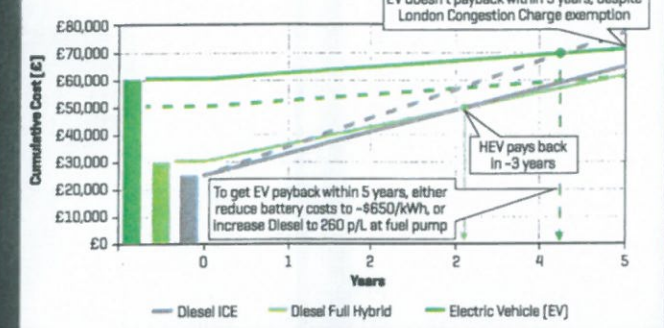
Like the previous scenario, the hybrid vehicle makes a financial return within its lifetime, in this case in just over three years. Despite the congestion charge exemption for such vehicles, the EV again fails to demonstrate a financial return within five years, based on current cost assumptions. In order for this situation to change, the cost of Li-ion cells would

Scenario B – City based supermarket delivery service

Scenario B: Carbon Payback



Scenario B: Financial Payback



Life cycle carbon emission and financial performance of the two low carbon and baseline vehicle respectively for scenario A and B.

have to fall to \$650/kWh or the price of diesel fuel increase to 260p/litre – subject to the combined impact of both of these changes, the EV would post a financial return in just over three years in comparison with the baseline vehicle.

Balancing cash and carbon accounting

The two scenarios presented highlight the challenge facing fleet operators in attempting to align their corporate social responsibility and commercial objectives, as Patterson explains: "Even with current incentives such as the waiver on the London Congestion Charge for low-carbon vehicles, in the case of each of these two realistic scenarios, a case cannot be made for full electrification on financial grounds alone. However, the sensitivity studies on fuel price and on battery cost demonstrate the marginal nature of this balance based even on current cost structures. Therefore, for technologists the question must be how to tackle the high upfront costs and carbon content of otherwise low-carbon vehicles. For business operators, the challenge is to ascribe a financial value to reductions in their carbon footprint such that the full advantages of low-carbon technologies can be properly evaluated."



Introducing a series on Meeting the Climate Challenge. For a close look at one option, biofuels, see "Green Dreams," page 38.

Never mind the steam spewing from a coal-fired power plant. The problem is what you can't see: greenhouse gases, mainly CO₂. Plants like this generate a quarter of human-kind's CO₂ emissions.

MITCH EPSTEIN, GETTY IMAGES

ESSAY BY BILL McKIBBEN

Carbon's New Math

To deal with global warming,
the first step is to do the numbers.

Here's how it works. Before the industrial revolution, the Earth's atmosphere contained about 280 parts per million of carbon dioxide. That was a good amount—"good" defined as "what we were used to." Since the molecular structure of carbon dioxide traps heat near the planet's surface that would otherwise radiate back out to space, civilization grew up in a world whose thermostat was set by that number. It equated to a global average temperature of about 57 degrees Fahrenheit, which in turn equated to all the places we built our cities, all the crops we learned to grow and eat, all the water supplies we learned to depend on, even the passage of the seasons that, at higher latitudes, set our psychological calendars.

Once we started burning coal and gas and oil to power our lives, that 280 number started to rise. When we began measuring in the late 1950s, it had already reached the 315 level. Now it's at 380, and increasing by roughly two parts per million annually. That doesn't sound like very much, but it turns out that the extra heat that CO₂ traps, a couple of watts per square meter of the Earth's surface, is

Global warming presents the greatest test humans have yet faced. New technologies and new habits offer some promise, but only if we move quickly and decisively.

enough to warm the planet considerably. We've raised the temperature more than a degree Fahrenheit already. It's impossible to precisely predict the consequences of any further increase in CO₂ in the atmosphere. But the warming we've seen so far has started almost everything frozen on Earth to melting; it has changed seasons and rainfall patterns; it's set the sea to rising.

No matter what we do now, that warming will increase some—there's a lag time before the heat fully plays out in the atmosphere. That is, we can't stop global warming. Our task is less inspiring: to contain the damage, to keep things from getting out of control. And even that is not easy. For one thing, until recently there's been no clear data suggesting the point where catastrophe looms. Now we're getting a better picture—the past couple of years have seen a series of reports indicating that 450 parts per million CO₂ is a threshold we'd be wise to respect. Beyond that point, scientists believe future centuries will likely face the melting of the Greenland and West Antarctic ice sheets and a subsequent rise in sea level of giant proportion. Four hundred fifty parts per million is still a best guess (and it doesn't include the witches' brew of other, lesser, greenhouse gases like methane and nitrous oxide). But it will serve as a target of sorts for the world to aim at. A target that's moving, fast. If concentrations keep increasing by two parts per million per year, we're only three and a half decades away.

Bill McKibben's 11th book on environmental topics, The Bill McKibben Reader: Pieces from an Active Life, will be published this winter.

So the math isn't complicated—but that doesn't mean it isn't intimidating. So far only the Europeans and Japanese have even begun to trim their carbon emissions, and they may not meet their own modest targets. Meanwhile, U.S. carbon emissions, a quarter of the world's total, continue to rise steadily—earlier this year we told the United Nations we'd be producing 20 percent more carbon in 2020 than we had in 2000. China and India are suddenly starting to produce huge quantities of CO₂ as well. On a per capita basis (which is really the only sensible way to think about the morality of the situation), they aren't anywhere close to American figures, but their populations are so huge, and their economic growth so rapid, that they make the prospect of a worldwide decline in emissions seem much more daunting. The Chinese are currently building a coal-fired power plant every week or so. That's a lot of carbon.

Everyone involved knows what the basic outlines of a deal that could avert catastrophe would look like: rapid, sustained, and dramatic cuts in emissions by the technologically advanced countries, coupled with large-scale technology transfer to China, India, and the rest of the developing world so that they can power up their emerging economies without burning up their coal. Everyone knows the big questions, too: Are such rapid cuts even possible? Do we have the political will to make them and to extend them overseas?

The first question—is it even possible?—is usually addressed by fixating on some single new technology (hydrogen! ethanol!) and imagining it will solve our troubles. But the scale of the problem means we'll need many strategies. Three years ago a Princeton team made one of the best assessments of the possibilities. Stephen Pacala and Robert Socolow published a paper in *Science* detailing 15 “stabilization wedges”—changes big enough to really matter, and for which the technology was already available or clearly on the horizon. Most people have heard of some of them: more fuel-efficient cars, better-built homes, wind turbines, biofuels like ethanol. Others are newer and less sure: plans for building coal-fired power plants that can separate carbon from the

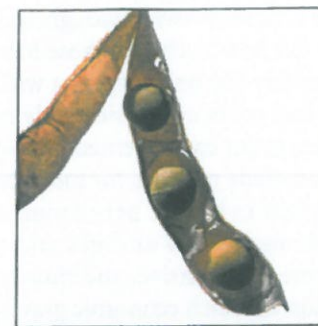
exhaust so it can be “sequestered” underground.

These approaches have one thing in common: They're more difficult than simply burning fossil fuel. They force us to realize that we've already had our magic fuel and that what comes next will be more expensive and more difficult. The price tag for the global transition will be in the trillions of dollars. Of course, along the way it will create myriad new jobs, and when it's complete, it may be a much more elegant system. (Once you've built the windmill, the wind is free; you don't need to guard it against terrorists or build a massive army to control the countries from which it blows.) And since we're wasting so much energy now, some of the first tasks would be relatively easy. If we replaced every incandescent bulb that burned out in the next decade anywhere in the world with a compact fluorescent, we'd make an impressive start on one of the 15 wedges. But in that same decade we'd need to build 400,000 large wind turbines—clearly possible, but only with real commitment. We'd need to follow the lead of Germany and Japan and seriously subsidize rooftop solar panels; we'd need to get most of the world's farmers plowing their fields less, to build back the carbon their soils have lost. We'd need to do everything all at once.

As precedents for such collective effort, people sometimes point to the Manhattan Project to

build a nuclear weapon or the Apollo Program to put a man on the moon. But those analogies don't really work. They demanded the intense concentration of money and intelligence on a single small niche in our technosphere. Now we need almost the opposite: a commitment to take what we already know how to do and somehow spread it into every corner of our economies, and indeed our most basic activities. It's as if NASA's goal had been to put all of us on the moon.

Not all the answers are technological, of course—maybe not even most of them. Many of the paths to stabilization run straight through our daily lives, and in every case they will demand difficult changes. Air travel is one of the fastest growing sources of carbon emissions around the world, for instance, but even many of us who are noble about changing lightbulbs and happy to drive hybrid cars chafe at the thought of not jetting around the country or the world. By now we're used to ordering take-out food from every corner of the world every night of our lives—according to one study, the average bite of food has traveled nearly 1,500 miles before it reaches an American's lips, which means it's been marinated in (crude) oil. We drive alone, because it's more convenient than adjusting our schedules for public transit. We build ever bigger homes even as our family sizes shrink, and we watch ever



SOYBEANS



WIND TURBINE



SOLAR PANEL



COMPACT FLUORESCENT BULB

CLOCKWISE FROM TOP LEFT: ROBERT CLARK; JORG GREUEL, GETTY IMAGES; ROBERT CLARK; VICTORIA SNOWBER, GETTY IMAGES

CARBON'S NEW MATH 35

bigger TVs, and—well, enough said. We need to figure out how to change those habits.

Probably the only way that will happen is if fossil fuel costs us considerably more. All the schemes to cut carbon emissions—the so-called cap-and-trade systems, for instance, that would let businesses bid for permission to emit—are ways to make coal and gas and oil progressively more expensive, and thus to change the direction in which economic gravity pulls when it applies to energy. If what we paid for a gallon of gas reflected even a portion of its huge environmental cost, we'd be driving small cars to the train station, just like the Europeans. And we'd be riding bikes when the sun shone.

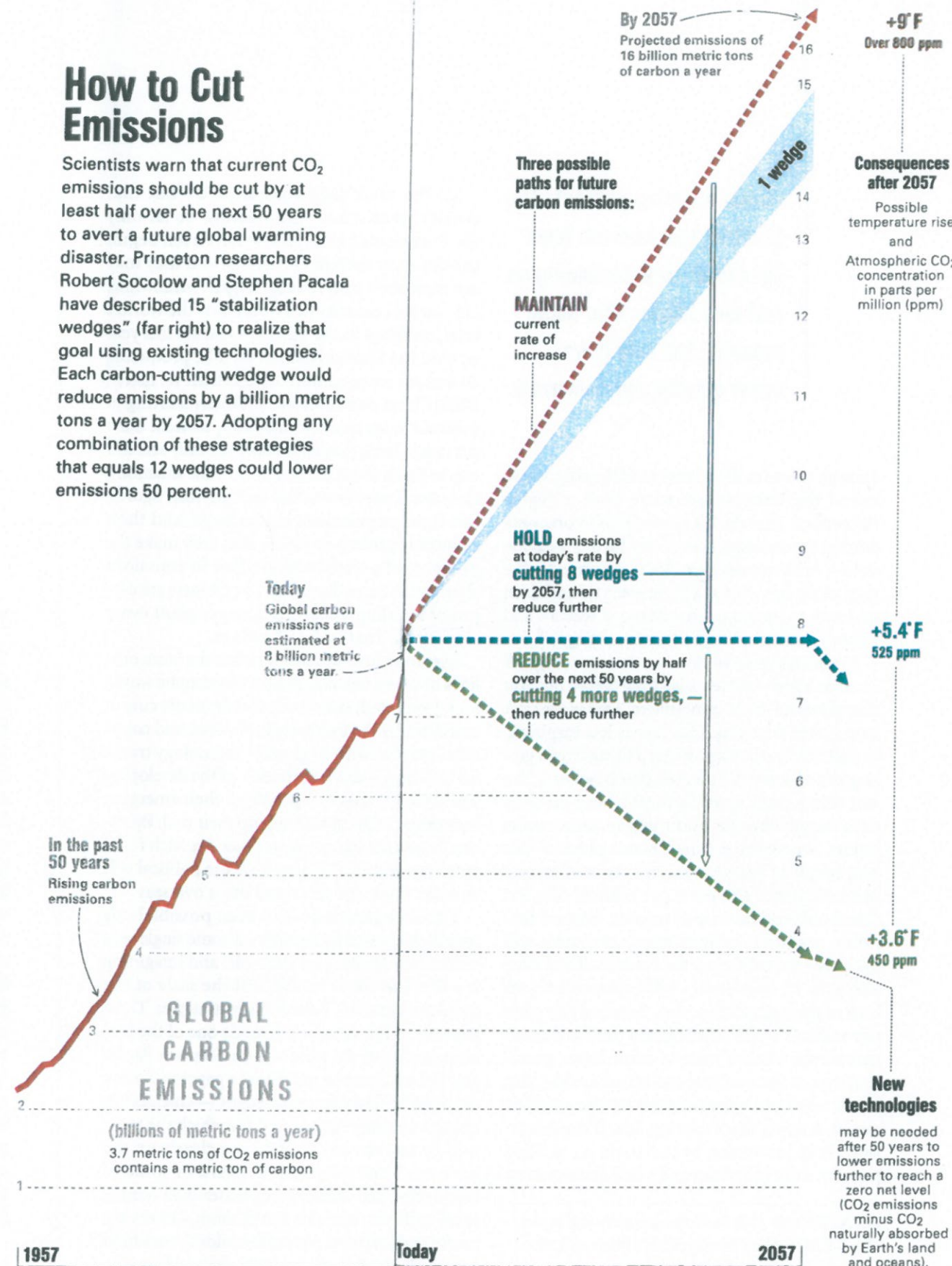
The most straightforward way to raise the price would be a tax on carbon. But that's not easy. Since everyone needs to use fuel, it would be regressive—you'd have to figure out how to keep from hurting poor people unduly. And we'd need to be grown-up enough to have a real conversation about taxes—say, about switching away from taxes on things we like (employment) to taxes on things we hate (global warming). That may be too much to ask for—but if it is, then what chance is there we'll be able to take on the even more difficult task of persuading the Chinese, the Indians, and all who are lined up behind them to forgo a coal-powered future in favor of something more manageable? We know it's possible—earlier this year a UN panel estimated that the total cost for the energy transition, once all the pluses and minuses were netted out, would be just over 0.1 percent of the world's economy each year for the next quarter century. A small price to pay.

In the end, global warming presents the greatest test we humans have yet faced. Are we ready to change, in dramatic and prolonged ways, in order to offer a workable future to subsequent generations and diverse forms of life? If we are, new technologies and new habits offer some promise. But only if we move quickly and decisively—and with a maturity we've rarely shown as a society or a species. It's our coming-of-age moment, and there are no certainties or guarantees. Only a window of possibility, closing fast but still ajar enough to let in some hope. □

Warming Trends For more on climate from National Geographic and NPR, visit ngm.com/climateconnections and npr.org/climateconnections.

How to Cut Emissions

Scientists warn that current CO₂ emissions should be cut by at least half over the next 50 years to avert a future global warming disaster. Princeton researchers Robert Socolow and Stephen Pacala have described 15 "stabilization wedges" (far right) to realize that goal using existing technologies. Each carbon-cutting wedge would reduce emissions by a billion metric tons a year by 2057. Adopting any combination of these strategies that equals 12 wedges could lower emissions 50 percent.



SOURCES: ROBERT H. SOCOLOW AND STEPHEN W. PACALA, PRINCETON UNIVERSITY (UPDATED REPORT); OAK RIDGE NATIONAL LABORATORY (GLOBAL CARBON EMISSIONS DATA); ICONS BY JONATHAN AVERY; GRAPHIC BY JUAN VELASCO, NGM ART