Scenarios are a tool for helping managers plan for the future — or rather for different possible futures. They help us focus on critical uncertainties. On the things we don't know about which might transform our business. And on the things we do know about in which there might be unexpected discontinuities. They help us understand the limitations of our 'mental maps' of the world — to think the unthinkable, anticipate the unknowable and utilise both to make better strategic decisions.

Exploring The Future

Energy Needs, Choices and Possibilities - Scenarios to 2050

# Energy Needs, Choices and Possibilities

## Scenarios to 2050

EXPLORING The Future

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# Energy Needs, Choices and Possibilities

## Scenarios to 2050

Global Business Environment
Shell International 2001

## Foreword

The ways in which we provide and use the energy the world depends on are bound to change greatly over the next 50 years, in response to three fundamental challenges:

- giving all people access to the benefits of efficient, commercial energy from which nearly a fifth of us are still excluded,
- meeting the expanding and shifting energy needs of an urbanising world as economic development raises the living standards of billions of people, and
- preventing the pollution which damages health, blights environments and threatens vital natural systems.

In Shell, we use long-term energy scenarios — looking out over 50 years — to help us understand how energy systems could change. The work is based on our world-wide experience in energy businesses, in serving energy consumers and in developing and applying technology. But such scenarios are not an exercise in prophecy. Rather they are designed to challenge our thinking so that we can make better business decisions today — helping us fulfil our commitments to our customers and society. It is in that spirit that we offer them as a contribution to public debate. We also know that by engaging with the views of others we improve our own understanding.

These scenarios focus on some key questions about how energy systems may develop, taking forward the broader-brush 'what if' questions of their 1995 predecessors. They reflect new knowledge and possibilities.

The two scenarios contrast an evolutionary progression from coal, to gas, to renewables (or possibly nuclear) against the potential for a hydrogen economy — supported by developments in fuel cells, advanced hydrocarbon technologies and carbon dioxide sequestration. They remind us that energy systems are dynamic, able to respond to changing conditions, choices and possibilities. They also suggest that the rise in human-induced carbon dioxide emissions can be halted within the next 50 years — leading to a stabilising of atmospheric carbon dioxide levels below 550 ppmv — without jeopardising economic development.

Governments have a key role in establishing the framework within which this can take place, although the scenarios highlight the impossibility of picking future technology winners with any certainty — particularly in what seems likely to be a highly innovative period in energy technology.

The scenarios explore uncertainties around the long-term role of gas, but highlight its key role as a bridging fuel. Expanding the use of gas is perhaps the most important immediate way of responding to the climate threat, as well as of improving air quality.

The future of our energy systems is vital for us all. We hope you find these scenarios thought-provoking and look forward to hearing your views.

Phil Watts

**Philip Watts**

**Chairman of the Committee of Managing Directors, Royal Dutch/Shell Group**

## We welcome your questions and views

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## Challenging assumptions with scenarios

**Scenarios are a tool for helping managers plan for the future – or rather for different possible futures. They help us focus on critical uncertainties. On the things we don't know about which might transform our business. And on the things we do know about in which there might be unexpected discontinuities. They help us understand the limitations of our 'mental maps' of the world – to think the unthinkable, anticipate the unknowable and utilise both to make better strategic decisions.**

**Scenarios are alternative stories of how the world may develop. They are not predictions – but credible, relevant and challenging alternative stories that help us explore 'what if' and 'how'. Their purpose is not to pinpoint future events – but to consider the forces which may push the future along different paths. They help managers understand the dynamics of the business environment, recognise new possibilities, assess strategic options and take long-term decisions.**

**Shell companies pioneered the use of scenarios for strategic planning in the 1970s and have used them for a wide range of studies. Shell planners have also been involved in developing scenarios with such bodies as the World Business Council for Sustainable Development and the Intergovernmental Panel on Climate Change (IPCC), as well as to help build a shared vision of the future in divided societies, such as South Africa in the early 1990s. Shell first developed long-term energy scenarios for the first half of the 21st century in 1995.**

**There is no limit to the stories we could tell about the future. Some scenario exercises – such as that recently carried out by the IPCC – create a wide range of alternative scenarios. Shell experience is that for developing our strategic thinking, it is more productive to focus on just two thought-provoking scenarios.**



## Context and key questions

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Three introductory sections analyse the forces that will affect the global energy system:

- the broad patterns underlying today's system which are likely to persist,
- forces which influence energy patterns but are unlikely to be fundamental in shaping long-term change, and
- three factors likely to be decisive: resources, technology, and social priorities.

The two scenarios *Dynamics as Usual* and *The Spirit of the Coming Age* consider different energy futures depending on the development, impact and timing of these forces.

Key questions explored in those scenarios include:

- when will oil and gas resources cease to meet rising demand, and what will replace oil in transport,
- which technology will win the race to improve the environmental standards of vehicles,
- how will demand for distributed power shape the energy system,
- who will drive the market growth and cost reduction of renewable energy sources, and how will energy storage for intermittent renewables like solar and wind be solved,
- how might a hydrogen infrastructure develop,
- how will emerging economies like China and India balance rapidly growing energy needs with rising import dependence and environmental effects,
- where will social and personal priorities lie and how will these affect energy choices?

Energy development has always depended on choices: by consumers, producers, governments and societies. This has brought an energy system based on those sources seen as most satisfactory in terms of cost, quality, reliability, security, convenience and social impact.

We appear to be entering a particularly innovative period with a wide set of possibilities for energy development and more than one path to a sustainable energy system. Advances in biotechnology, materials technology such as carbon nano-fibres, and information and communications technology will support development of bio-fuels, fuel cells, new energy carriers such as hydrogen, micro-power networks, and new generations of solar technologies.

The overarching question is 'what energy needs, choices and possibilities will shape a global energy system which halts the rise in human-induced carbon dioxide emissions within the next 50 years – leading to a stabilising of atmospheric carbon levels below 550 ppmv[1] – without jeopardising economic development?'

**1** 550 ppmv has been chosen as a level that has been often cited as a safe maximum. We do not, of course, know – and probably never will – what is the right level. Decisions will always have to be made under great uncertainty and adjusted as scientific understanding develops.





## 1995 Long-Term Energy Scenarios

**The 1995 Long-Term Energy Scenarios recognised that the energy system was anything but static. Normal market dynamics could reduce greenhouse gas emissions in two ways – by advancing energy efficiency or making renewable energy competitive. Converging technology advances would enable increasing efficiency, for example by developing 'supercars'. Renewables would start by supplying niche markets, reduce costs with experience – like previous technologies – and eventually compete with conventional fuels, as depleting resources raised fossil fuel prices. The cost of exploiting increasingly remote resources would make large-scale reliance on coal uneconomic. Nuclear energy would be hampered by costs and public acceptability.**

**The scenarios explored the extremities of two 'what if' questions. What if energy efficiency improved at the maximum historic rate (*Dematerialisation*)? And what if renewables were able to expand supply as fast as oil early in the 20th century (*Sustained Growth*)? The latter scenario explored the upper limit of potential renewable energy growth and led to the oft-quoted estimate of 50% of world primary energy being met by renewables by 2050. This estimate is among the highest potential renewables share and lies outside the range of the new IPCC scenarios.**

## Present in the future

Energy is essential for economic development and rising living standards. Changes in the energy system mark transitions in the economic and social development of countries and societies – as they climb the energy ladder.

The first and most important step is substituting commercial for traditional fuels. Perhaps one billion people worldwide still rely mainly on biomass fuels and animal wastes. After that there is a strong – but constantly changing – relationship between income and energy demand. When per capita GDP (on a purchasing power parity basis) reaches some:

- $3,000 – demand explodes as industrialisation and personal mobility take off,
- $10,000 – demand slows as the main spurt of industrialisation is completed,
- $15,000 – demand grows more slowly than income as services dominate economic growth and basic household energy needs are met,
- $25,000 – economic growth requires little additional energy.

As basic energy needs are met, consumer priorities shift to other, often less energy-intensive, goods and services, pointing to eventual saturation of energy needs. For example, in the OECD:

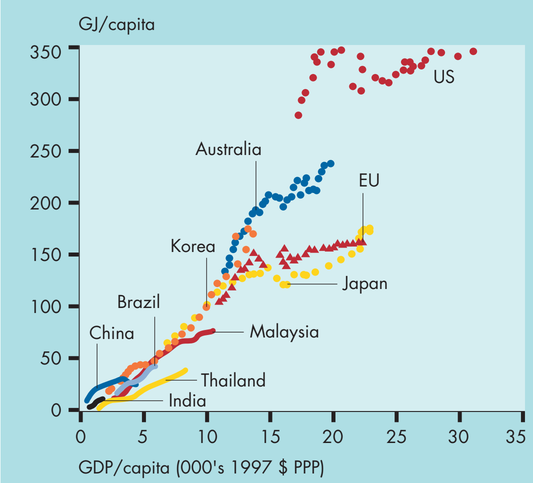
- the market for major energy consuming household appliances is largely saturated, with little scope to further mechanise household chores,
- car ownership shows signs of stabilising at just over one for every two people when average income reaches some $30,000,
- demand for more living space is constrained by considerations of access to urban amenities and of travel times.

Newly industrialising countries are able to climb the ladder more quickly, thanks to the proven technologies with lower costs from earlier development elsewhere. But more efficient technologies mean they also require less energy at every stage.



Per capita primary energy consumption grows with income in a similar pattern across countries and time. Around $15,000 per capita ($1997 PPP) the relationship shifts as less energy-intensive services dominate economic growth. There are signs of saturation beyond $25,000 and evidence that later developers require less energy.

**Climbing the Energy Ladder**




*Source: IMF, BP*

1

The importance of technological improvement in shaping energy needs is illustrated by the striking increases in steam engine efficiency since the early 18th century – reducing coal needs by a factor of 25.

The latest technology is often more than twice as efficient as the installed average and a 25% improvement in cost-effective efficiency is typically available – the natural outcome of continuing advances and long-lived capital stock. How quickly improvements are introduced depends on their cost relative to the price of energy. But – with energy now accounting for less than 5% of average OECD household expenditures and less than 2% of production costs for most OECD economic activity – accelerated turnover of equipment is unlikely without government intervention.

Consumers will pay a premium for superior attributes. Oil was twice the price of coal when its efficiency, convenience and cleanliness – harnessed to the internal combustion engine – drove a transition from coal. The convenience of natural gas makes it the preferred heating fuel despite higher costs. Evolving energy supplies have steadily decarbonised. But this has been a by-product of the pursuit of convenience, quality and cleanliness, not a conscious effort to reduce carbon dioxide emissions.

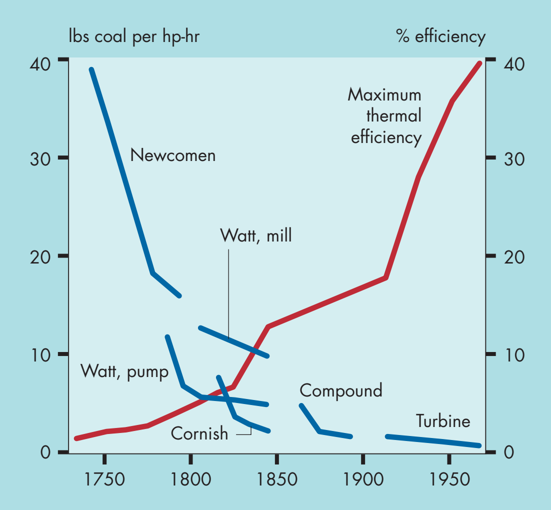
Environmental concerns shift with wealth. They also compete with – and often appear to conflict with – other priorities, such as employment. In wealthy societies the debate is generally about competing priorities not absolute affordability. But attitudes can shift rapidly if emerging technologies offer easier solutions. Real or perceived environmental crises can accelerate technology advances. The ‘killer smog’ of 1952 was the trigger for banning urban coal emissions in the United Kingdom.

Governments have always played an important role in energy markets because energy has been viewed as a strategic commodity and, more recently, as an essential public service. But these actions are rarely fundamental. New fuels or technologies succeed only where they provide new or superior energy services for consumers.



Advances in steam engine technology since 1750 have reduced coal consumption per horsepower hour 25-fold.

**Technology Cuts Energy Needs**




*Source: Technology and Change, Grubler, 1998 (from Ayres, 1989)*

1

Shifting consumption patterns typically require expensive and time-consuming infrastructure development. If there is pressure to change, history suggests fuels can achieve a maximum of 10-12% a year compound growth after reaching 2% market share. When capital-intensive incumbents are challenged, prices can remain very low for extended periods. And the faster a new technology grows the more it pushes up input costs, such as land or silicon. The large number of competing fuels today will make it difficult for new technologies like renewables to achieve high growth simply on the basis of cost.

Consumers in industrialised countries expect very high quality energy:

- available on demand in the intensity required,
- safe, clean and portable,
- ubiquitous but unobtrusive.

Most of the world's people have more fundamental needs. One billion people have not yet reached the bottom rung of the energy ladder, while more than three billion are just meeting basic energy requirements.



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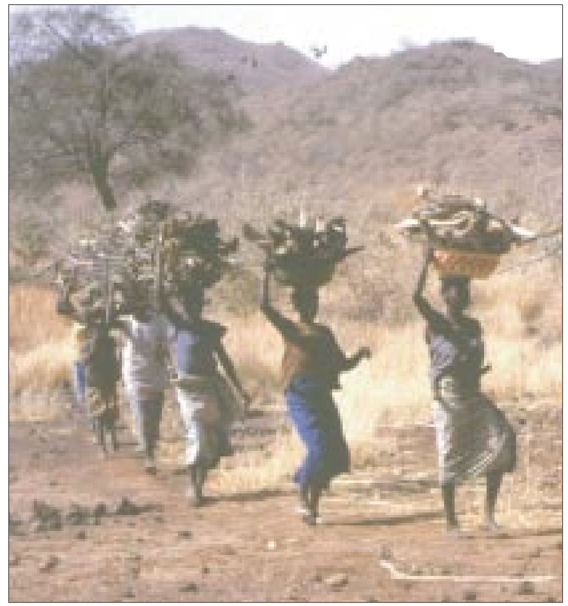
Portable, safe and comparatively clean energy is available on demand in industrialised countries.



Rural energy consumers in developing countries often have to make do with energy simply being portable.

1

## The social and economic context

Some powerful forces – demographics, incomes, market liberalisation and demand – will shape the socio-economic context for energy, without being fundamental in energy transitions.

Recent UN population forecasts point to 8.5 billion people by 2050 and a maximum global population of 10 billion by 2075. Populations are ageing. Even in developing countries with young populations, age profiles by 2050 should resemble the OECD today. Over 80% of people are likely to live in urban environments by 2050. **Demographic** uncertainties are unlikely to be fundamental in shaping energy developments.

Annual economic growth of 3.5% over the next 50 years – less than in the past half century – would bring widespread affluence, raising global average per capita **incomes** above $20,000 by 2050. The rapid phase of energy demand growth would already have occurred in most countries and the energy system would have been through its severest test.

There are two clear trends in **consumer preferences** which will influence future energy supplies – an increasing stress on cleanliness, for environmental and health reasons, and the growing value placed on flexibility, saving time and avoiding disruptions.

As well as driving greater efficiency, **liberalised markets** are breaking down boundaries between formerly separate markets such as gas and power. But more fundamentally, this increases energy possibilities. This will accelerate long-term trends of rising fuel quality and the dominance of electricity – driven by consumer demands for cleaner, more flexible and convenient fuels.





Global primary **energy demand** could ultimately saturate, outside the scenario period, at around 200 GJ per capita – some 15% above present EU consumption – with any additional demand offset by increased efficiency. On this basis, the world would be consuming three times as much energy as now by 2050. If investing in efficiency – for cost or environmental reasons – becomes more attractive than increasing supplies, saturation could occur at around 100 GJ per capita. Efficiency could more than double simply through widespread diffusion of existing and anticipated technologies[2]. Under these conditions energy consumption would be just over twice what it is now by 2050. The difference between the potential bounds is significant, but insufficient to determine the energy path, only its timing.

**2** Various studies suggest that a fourfold, or even greater, improvement in efficiency is possible.

1

## Three fundamental drivers

Three factors have the potential to bring about fundamental changes in the energy system.

The first is **energy resource scarcity**. This occurs rarely at a global level, when demand growth cannot be met because resources are limited or the costs of new production capacity are too high. It would inevitably trigger discontinuity in the energy system.

Coal will not become scarce within this timescale, though resources are concentrated in a few countries and will become increasingly complex and distant from markets. Costs of exploiting and using them will eventually affect coal's competitiveness.

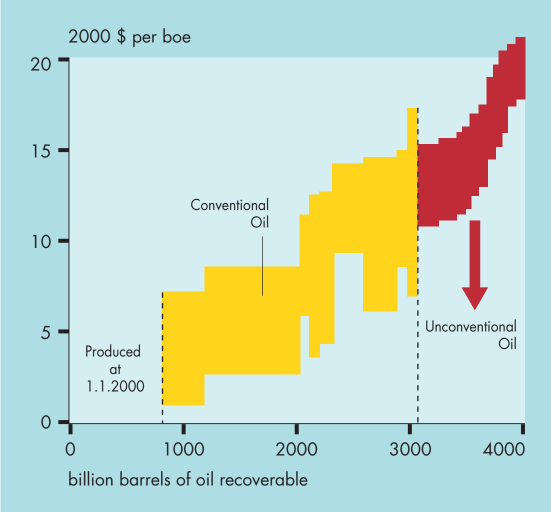
Oil production has long been expected to peak. Some think this is now imminent. But a scarcity of oil supplies – including unconventional sources and natural gas liquids – is very unlikely before 2025. This could be extended to 2040 by adopting known measures to increase vehicle efficiency and focusing oil demand on this sector. Technology improvements are likely to outpace rising depletion costs for at least the next decade, keeping new supplies below $20 per barrel. The costs of biofuels and gas to liquids should both fall well below $20 per barrel of oil equivalent over the next two decades, constraining oil prices.

Gas resource uncertainty is significant. Scarcity could occur as early as 2025, or well after 2050. Gas is considered by many to be more scarce than oil, constraining expansion. But the key issue is whether there can be timely development of the infrastructure to transport remote gas economically.



The cost of new oil supply ranges from $5/bbl for some Middle East resources to around $17/bbl for remote non-OPEC resources. Unconventional oil has fallen below $20/bbl. Substitutes should fall below $20/boe by 2020, constraining oil prices.

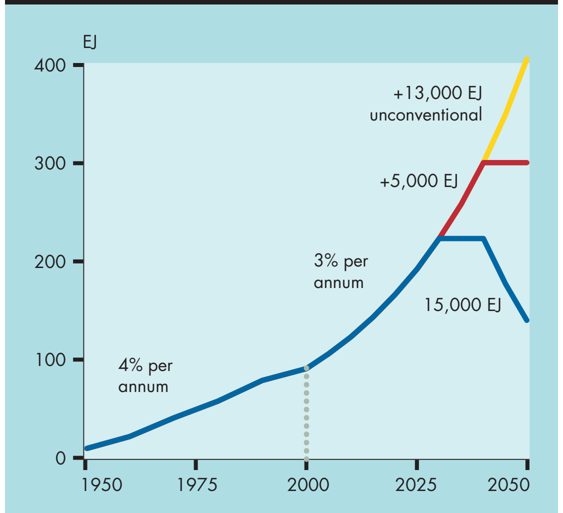
### Falling Costs Constrain Oil Prices




*Source: Shell 2000, USGS 2000 mean resource*

The ultimately recoverable conventional gas resource is highly uncertain. Estimates range from 15,000 EJ (mean USGS estimate) to 20,000 EJ (5% probability USGS). Unconventional gas resources could add another 13,000 EJ. The resource could support 3% annual growth for at least 25 years.

### Gas Resources are Uncertain




*Source: based on USGS mean estimates, 2000 and IPCC 2000 for unconventional*

1

Nuclear energy expansion has stalled in OECD countries, not only because of safety concerns but because new nuclear power is uncompetitive. Even with emission constraints, the liberalisation of gas and power markets means this is unlikely to change over the next two decades. Further ahead, technology advances could make a new generation of nuclear supplies competitive.

Renewable energy resources are adequate to meet all potential energy needs, despite competing with food and leisure for land use. But widespread use of solar and wind will require new forms of energy storage. Renewable energy has made few inroads into primary energy supply. Athough the costs of wind and photovoltaic sources have fallen dramatically over the past two decades, this is also true for conventional energy.

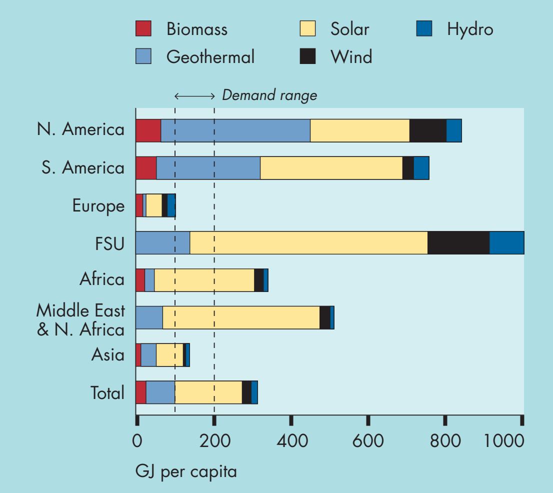
The second driving force for discontinuity in energy patterns is **new technology**.

A technology that offers superior or new qualities, even at higher costs, can dramatically change lifestyles and related energy use. Widespread introduction of electricity in the early twentieth century prompted fundamental changes in production processes, business organisation and patterns of life. Coal-fired steam engines powered the early stages of industrialisation, replacing wood, water and wind. The internal combustion engine provided vastly superior personal transport, boosting oil consumption. The combined cycle gas turbine has become the technology of choice for power generation – greatly increasing the demand for gas, already the preferred heating fuel.



There is potential useable renewable energy – primarily geothermal and solar – to supply some 250 GJ each to 10 billion people, adequate for needs if intermittent sources can be stored. Europe and Asia, with perhaps only 100 GJ per capita, could require imports.

**Renewables Could Meet Energy Needs**




*Source: adapted from UN 2000, WEC 1994, and ABB 1998.*
*Figures based on 10 billion people*

Two potentially disruptive energy technologies are solar photovoltaics, which offer abundant direct and widely distributed energy, and hydrogen fuel cells, which offer high performance and clean final energy from a variety of fuels. Both will benefit from manufacturing economies but both presently have fundamental weaknesses.

## Rampant innovation offers new possibilities

**Since the beginning of the Industrial Revolution we have passed through two major technology waves – and are now in our third. Each is associated with preferred energy forms.**

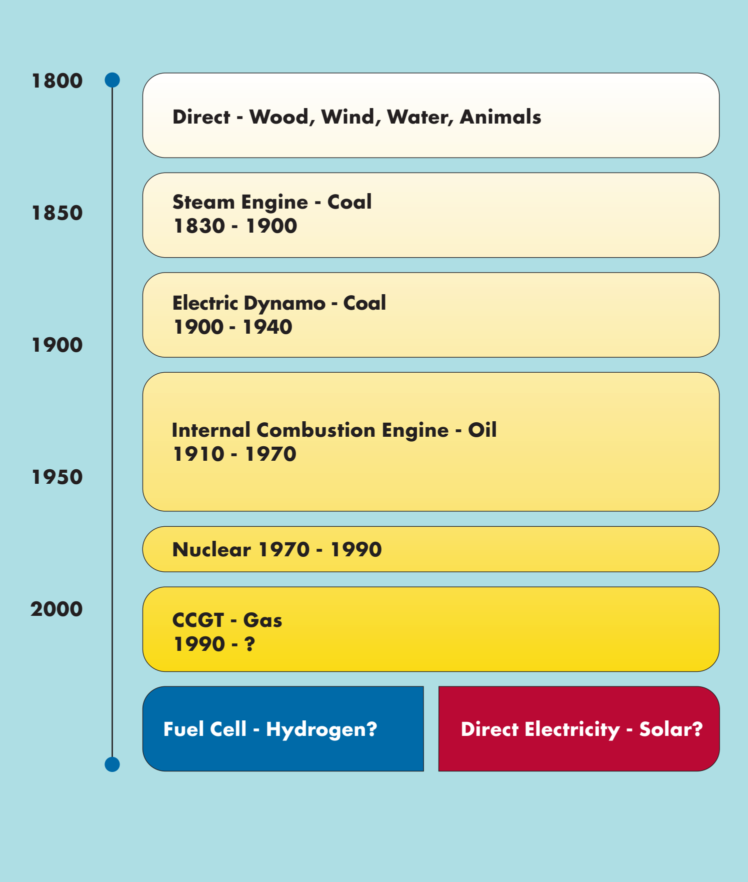
**With more engineers and scientists, and new ways of analysing information and sharing knowledge, this wave promises to be a strong promoter of innovation. We are entering a design era, supported by computing and communication technologies, with much greater interaction between previously separate disciplines. For example, computing developments contributed to decoding the human genome. We can expect a surfeit of 'disruptive technologies'.**

**Typically it has taken 25 years after commercial introduction for a primary energy form to obtain a 1% share of the global market. In OECD countries the average car lasts 13 years. The third wave could surprise everyone, with new possibilities including such things as nanotechnology and alternative energy forms. By 2050 the energy industry will be very different – in ways difficult to comprehend today.**



Five energy innovations, starting with the steam engine in the nineteenth century, have fundamentally affected the energy system. Superior services from new end-use equipment has been the key driver, not fuel availability. Two potential future discontinuities are new solar photovoltaic and hydrogen fuel cells.

## A Succession of Energy Technology Discontinuities



Fuel cells[3] require new fuelling infrastructure, while photovoltaics need new forms of storage as well as significant cost reductions. Do they provide sufficiently superior qualities – beyond environmental benefits – to induce consumers to pay a premium and trigger widespread adoption?

> **‘Fuel cell research is to be strongly recommended as a route to protecting the earth’s resources’**
>
> *Professor Wilhelm Ostwald, first meeting of the Bunsen society, 1897*

Picking winners has always been difficult. It is particularly so in a period of innovation and experimentation. Government efforts to accelerate adoption of a particular technology or push down a set path may be counterproductive, as may have happened with nuclear.

The third key influence on the future energy system is **social and personal priorities.**

Energy choices are ultimately social choices. Government and public attitudes towards energy security or self-sufficiency will, for example, influence the penetration of natural gas into Asian and European markets. It could also be the driving force in government support for renewable energy.

Personal choices – related to values, the environment and lifestyles – influence the energy system. Affordability is not the key constraint in OECD countries. And, while carbon abatement will influence the energy system, it need not determine the path. Many options exist for reducing greenhouse emissions, often linked to local air quality improvement.

When concerns prompt demands for change, much depends on what technologies or resources are readily available. Timing can make the difference between evolutionary or revolutionary solutions to problems like climate change.

3 The possibilities of fuel cells have been pursued for over a century – Shell undertook extensive research in the 1960s and 70s – but they are only now becoming viable.





Picking winners is difficult. The early winners of the automobile engine race in 1900 were steam and electric power, not internal combustion. Henry Ford’s mass production introduced a decisive new factor.

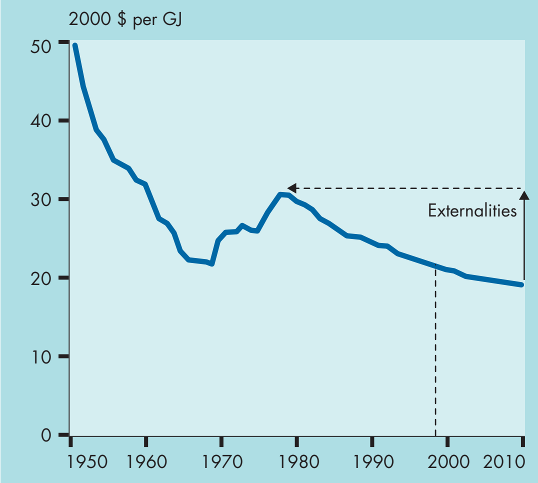
### The “Correct” Choice is Rarely Obvious

Automobile Options in 1900

| **Features** | **Steam** | **Electric** | **Internal Combustion** |
|---|---|---|---|
| Technology | familiar | simple | new |
| Quality | reliable<br>low-polluting | quiet<br>non-polluting | noisy<br>polluting |
| Starting | acceptable | easy | difficult crank |
| Fuel | hardware stores | slow recharge | hardware stores |
| Range | high (kerosene) | low | high (fuel density) |
| Wild Card | damage to roads<br>easily stuck | | Henry Ford (low cost)<br>petroleum industry |

Affordability is unlikely to be the decisive issue affecting fuel change in OECD countries. Adding the estimated cost of emission externalities would only bring US residential electricity prices in 2010 back to 1980 levels, when incomes were half as great.

### Affordability is Not the Issue




*Source: Edison Electric Institute, 1988, US EIA Forecasts to 2010 under Liberalisation, 1999 and Pace University, Environmental Costs of Electricity Externalities, 1990*

## Two scenarios

Demographics, urbanisation, incomes, market liberalisation and energy demand are all important factors in shaping the energy system but are not likely to be central to its evolution. By contrast, the availability of **energy resources** and, in particular, potential oil scarcity in the second quarter of the century, followed by gas some time later, will transform the system. What will take the place of oil – an orderly transition to bio-fuels in advanced internal combustion engines or a step-change to new technologies and new fuels?

Will incumbent **technologies** continue to become more efficient, meeting the challenge of delivering cleaner and more convenient energy? Or will radical new ones have the superior qualities to gain markets quickly?

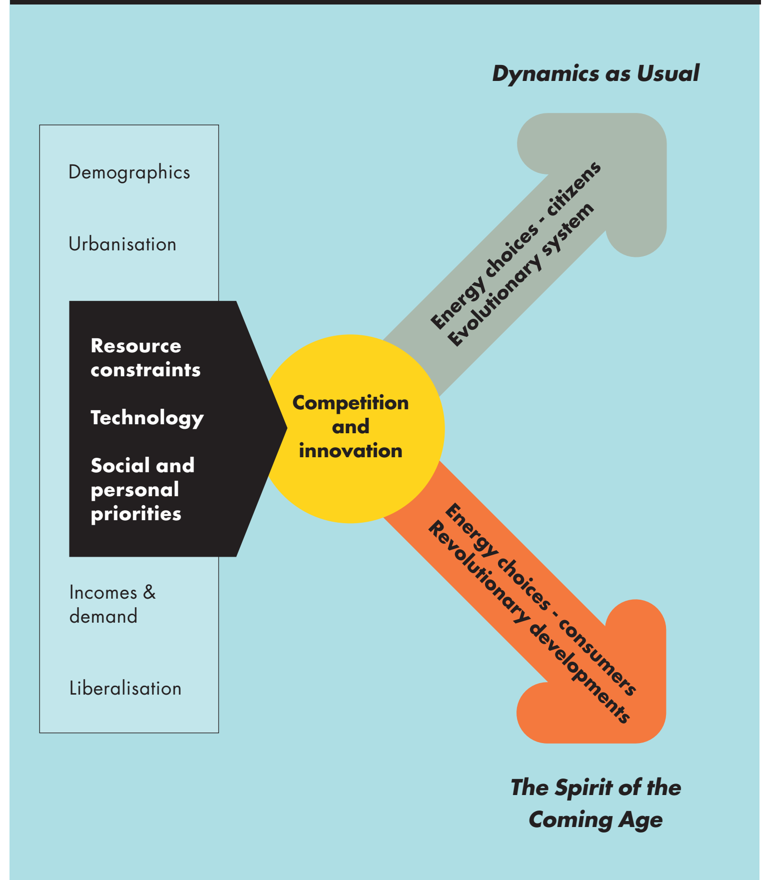
How will shifting **social and personal priorities** shape the energy system? Will it be pushed by governments on behalf of citizens concerned about common goods such as security and environment? Or will it be pulled by consumer demands for clean, convenient and flexible energy services?

And how will the competitive drive of incumbent and new suppliers respond to challenges to improve, innovate and create new energy possibilities?

Can the long-term challenge of creating an energy system capable of supporting increasing affluence without causing serious environmental damage – particularly to climate systems – be met? There are good reasons for thinking that it can – although this depends on views about what constitutes safe atmospheric carbon concentrations. A sustainable, affordable, minimal emission energy system is feasible. The issue for our scenarios is what energy needs, choices and possibilities will shape this?



**Energy Branching Points**



# Dynamics as Usual

A world where social priorities for 'clean', 'secure' and, ultimately 'sustainable' energy shape the system

## Dynamics as Usual

*Dynamics as Usual* is a world where social priorities for 'clean', 'secure' and, ultimately, 'sustainable' energy shape the system. But it is a world of shifting social priorities, of conflicting interests, intense competition among suppliers, and a wide range of maturing and emerging technologies. The transition to a sustainable, but increasingly diverse and complex, energy system is far from smooth.

### Social priorities

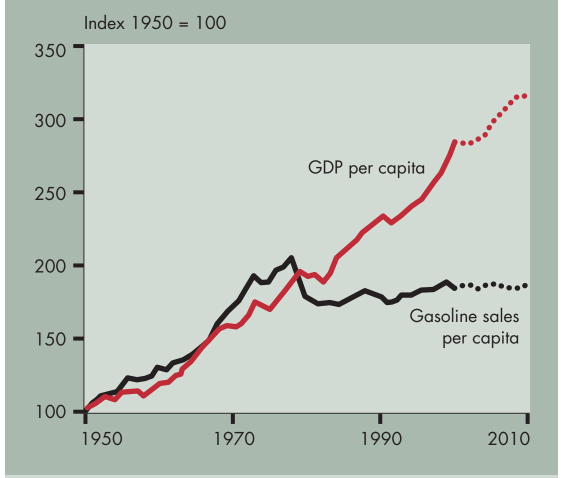
This scenario begins with major developing countries, such as China, experiencing rapid economic growth with explosive demand for transport, electricity and related infrastructures. Liberalisation and information technologies allow knowledge to be transferred more easily, enabling emerging economies to climb the energy and technology ladders more quickly and efficiently. By contrast, little extra energy is needed to support OECD economic growth and domestic needs. In all markets, advances in communications and materials technologies enable extraordinary productivity gains, reducing material and energy needs.

Many intangible factors determine the success of energy sources. In the industrialised world where consumers take energy supplies for granted, one factor for ageing populations is the focus on health and the environment. Public concerns about local air quality and climate drive ever tightening environmental standards. Companies look for competitive advantage by developing and marketing a range of 'clean' fuels that reduce emissions. Because energy costs are a relatively small element in household budgets, paying a premium for such fuels is widespread in wealthy countries. And in emerging markets the rapidly growing numbers of 'middle class' citizens increasingly demand action to reduce environmental problems related to low quality fuels and inefficient vehicles.



Since the sharp reduction in US demand in the early 1980s due to CAFE standards, per capita US gasoline consumption has risen by only 7% while per capita income has grown 50%.

**US Gasoline Demand Decouples from Income**




Source: US EIA, 2000

**Incumbent technologies respond**

Concerns about supply security complement the focus on health and the environment in stimulating greater energy efficiency. This prolongs the life of existing technologies, particularly the internal combustion engine. Developments bring a range of advanced internal combustion and hybrid engines, using as little as a third of the fuel to deliver the same quality ride. In time, they cost less than the alternative conventional vehicles. Fuel cell vehicles are first introduced in 2005 but fuelling inconvenience and consumer indifference limit their use to fleets. A similar indifference meets stationary fuel cell applications.

From 2010 to 2015 the spread of super-efficient vehicles causes turmoil in oil markets, and keeps prices weak. But markets eventually firm with growing demand for transport and heating fuels in developing countries. Price pressures also spur advances in oil recovery techniques expanding recoverable reserves. Oil demand grows steadily – although weakly – for another 25 years.

**Dash for gas**

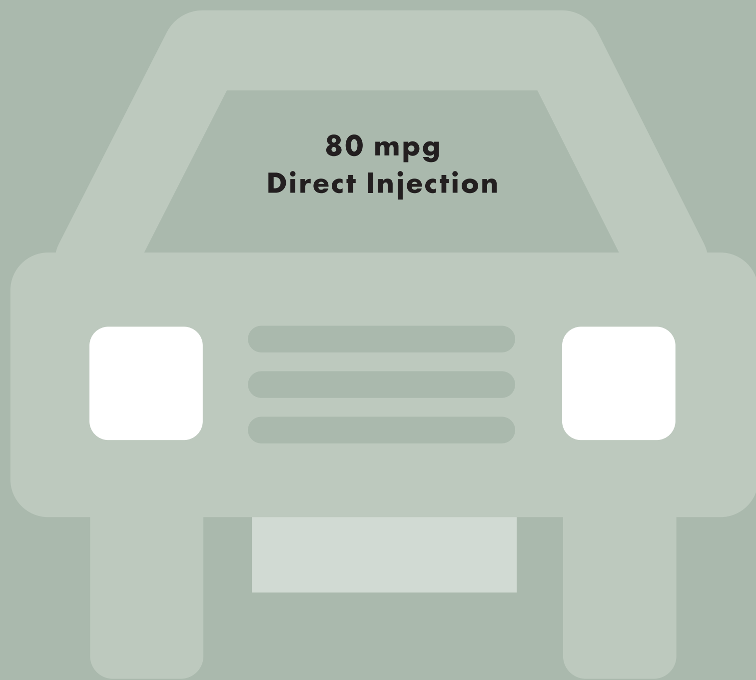
Natural gas use expands rapidly early in the century. New power generation is predominantly gas fuelled – wherever gas is available – and accounts for three-quarters of incremental OECD capacity up to 2015. This is because of the low cost, high efficiency and low emissions of combined-cycle gas turbines (CCGT) which produce negligible amounts of sulphur dioxide and half the carbon dioxide of advanced coal steam plants.

As markets are liberalised, fuel subsidies and pollution exemptions for coal-fired power stations become increasingly untenable. After 2010, the two-thirds of US coal plants over 40 years old are replaced, largely by gas. New nuclear plants have trouble competing in price sensitive deregulated markets. Most existing nuclear capacity is maintained. But, with little support for public or private investment in technologies which could remake it as a premium clean fuel, nuclear steadily loses market share in





Advanced internal combustion engines and hybrid engine configurations have the potential to deliver significant improvements in fuel efficiency – providing the same ride for half to one-third the fuel of current vehicles.




**‘Rumors of my death are greatly exaggerated’**

**Mark Twain**

OECD countries. It only expands – cautiously – in some developing ones. Public protests against new nuclear plants are not confined to rich countries.

China reacts to the rising costs and logistical complexity of ever expanding coal supply from its northern regions by initiating major gas import projects. Pan-Asian and Latin American gas grids emerge shortly after 2010. Significant LNG trade increases supply and enhances gas competitiveness.

Traditional oil exporters such as Iran, Mexico and Indonesia develop gas exports to reduce budget deficits. Gas is increasingly seen as another source of revenue rather than competition for oil. Middle East producers eventually join in to avoid being shut out of markets.

By 2010 gas has truly overtaken coal and by 2020 it is challenging oil as the dominant source of primary energy. However, because it is imported by many users, there is growing unease about supply security. Uncertainty about the availability of long-term resources and fear of political disruption in supplying countries start to constrain expansion. Liberalisation has also reduced buyer interest in long term contracts, while tough competition has kept gas and power prices low, affecting the development of major cross-border pipelines.

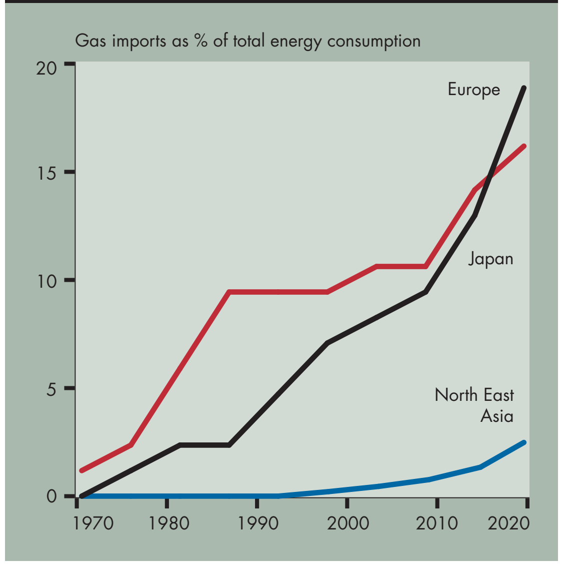
**Boom and bust for renewables**

In the first two decades of the century, renewable energy grows rapidly in OECD countries, within the framework of established electricity grids and strong government support. The costs of wind energy continue to fall as turbines exceed 3 MW. Deregulated markets provide opportunities for branded 'green energy', which gain 10% of demand in some regions. The commissioning of a 200 MW photovoltaic manufacturing plant in 2007 dramatically cuts the costs of solar energy, sparking consumer interest.



Natural gas imports grow significantly by 2020 – from 7% to 20% of total energy consumption in the EU, from 9% to 16% in Japan, and from 1% to 3% in North East Asia.

**Rising Gas Security Concerns**



Governments support a spread of renewable technologies to address public concerns about health, climate and supply security. Renewables experience more than 10% compound growth – with photovoltaic solar and wind growing at over 20% a year. By 2020 a wide variety of renewable sources is supplying a fifth of electricity in many OECD markets and nearly a tenth of global primary energy. Then growth stalls.

Rural communities that were willing to support the installation of a few windmills reject thousands. Wind farms must move to increasingly remote locations, driving up costs. Logistics, space constraints and environmental concerns prevent large-scale development of biomass electricity. It is increasingly difficult to gain approval for major renewable energy developments.

> **“The High Moor wind project would be insignificant, unreliable and overwhelmed by pollution from other countries.”**
>
> *Durham County Council rejection of wind farm application, 1999*

Stagnant electricity demand in OECD limits opportunities for expansion. Although the public supports renewables, most are unwilling to pay premium prices. In spite of significant cost improvements, photovoltaic power gains only niche markets. And with little progress on energy storage, concerns about power grid reliability block further growth of wind and solar energy.

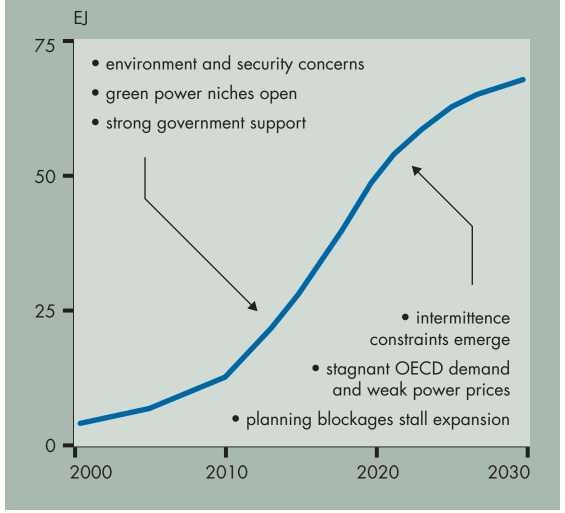
Developing countries, stimulated by OECD activities, expand renewable sources from 2010. There is a particular focus on wind power in China and India. Waste biomass is harnessed to provide rural energy, although this opportunity diminishes as rural incomes rise. However, renewables do not fully compete with low-cost conventional resources. Concerns about pollution stimulate more efficient and competitive coal-fired power generation. China and India also maintain energy diversity by supporting hydro and nuclear development.





Renewable energy grows strongly within established power grids to 2020, with government support and niche consumer interest. It then stalls with stagnant OECD electricity demand, unresolved intermittent energy storage and planning barriers.

**A Tale of Two Eras**
Renewable Growth and Plateau



With stagnating demand, renewable equipment prices collapse and several companies go bankrupt. New investment stagnates. The boom has spawned a set of diverse technologies – for wind, solar, biomass and geothermal – that have benefited little from each other's advances.

### All change from 2025

As renewables stagnate and gas security concerns grow, it is not clear what will fuel future energy supplies. Governments face a dilemma. Should they support crash programs to commercialise new nuclear technologies or hope for breakthroughs in solar energy storage or biofuels? Nuclear makes a partial comeback, particularly in Asia. Investing in energy efficiency buys time.

The energy system has become a diverse and complex mix of fuels and technologies. No technology/fuel combination is obvious as the dominant source of future supply, while increasingly stringent environmental standards start to exhaust the capacity of established technologies to meet them.

### The oil transition and renewables renaissance

As oil becomes scarce, around 2040, advances in biotechnology plus vastly improved vehicle efficiency bring a relatively smooth transition to liquid biofuels and low cost modification of the existing transport infrastructure. Biomass plantations, previously developed for power supply, are converted to transport fuel supply.

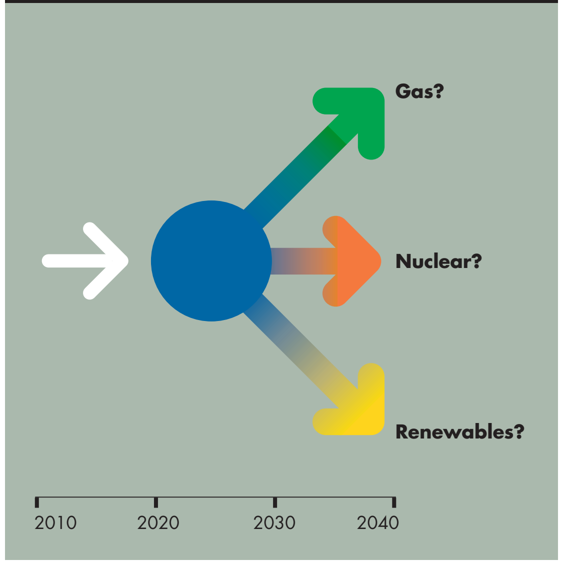
Since 2025 when the first wave of renewables began to stagnate, biotechnology, materials advances and sophisticated electric network controls have enabled a new generation of renewable technologies to emerge. The most important is organic and thin film embedded solar systems. A range of commercial solutions emerge to store and utilise distributed solar energy. By 2050 renewables reach a third of world primary energy and are supplying most incremental energy.





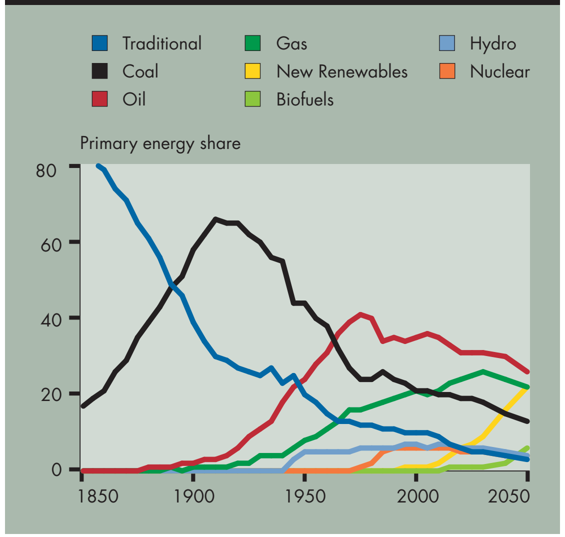
A fundamental choice is necessary – use more gas and increase import dependence, continue with inadequate intermittent renewable energy or push for commercialisation of new nuclear technologies.

**Choices Around 2025**




Energy supplies continue to evolve from high- to low-carbon fuels and towards electricity as the dominant energy carrier – from increasingly distributed sources – driven by demands for security, cleanliness and sustainability.

**Energy Transitions**
***Dynamics as Usual***



*Dynamics as Usual* highlights the key drivers of resource scarcity, environment and security concerns, competitive responses by incumbent technologies and competing societal priorities.

Looking back from 2050 the energy transition looks to be a continuation of past dynamics. Societal demands for cleaner, more convenient energy drive a gradual shift from high- to low-carbon fuels, and towards electricity as the energy carrier. The path towards a range of new renewables is relatively direct – supported by strong gas growth in the medium term – but only after advances in energy storage and the development of a next generation of renewables around 2025. By 2050 renewables could account for a third of world primary energy and be supplying all incremental energy. But underlying this transition is a process of intense competition, maturing new technologies and shifting social priorities, which makes the transition anything but smooth – that is to say *dynamics as usual*.





**Timeline** ***Dynamics as Usual***

| | |
|---|---|
| **2005** | **Hybrid vehicles proliferate with "CARB" pushes** |
| **2010** | **"Dash for Gas"; Renewable pump priming** |
| **2015** | **Oil price shock triggers resource expansion** |
| **2020** | **OECD renewables stall at 20% of electricity supply**<br>**Gas security concerns emerge** |
| **2030** | **New nuclear stalls**<br>**Next generation of renewables emerges** |
| **2040** | **Oil scarcity drives biofuels expansion** |

# The Spirit of the Coming Age

A world in which superior ways of meeting energy needs are developed to meet consumer preferences.

## The Spirit of the Coming Age

In *The Spirit of the Coming Age* superior ways of meeting energy needs are developed to meet consumer preferences. This is a world of experimentation and many failures. It is the story of a solution that triggers a technology revolution and a reminder that discontinuities can arise from seemingly mundane parts of the energy system.

In the early twentieth century a new engine technology, coupled with a portable and dense fuel, transformed transportation. This revolution started with fuel in a box, sold in local hardware stores, adequate for limited travel along the few paved roads. Efficiency considerations drove development of today's fuelling infrastructure – now a valuable economic asset as well as a barrier to change.

A century later, mobility is seen as one of the keys to the freedom, flexibility, convenience and independence that people want, and increasingly expect. Time is precious. Information and communication technologies dominate, creating a feeling of continuous movement even when people take advantage of the internet to stay put.





In 1908 a new engine using a highly dense fuel was appearing on roads already full of horse drawn carriages.

The new engine was initially powered by fuel in a box, sold in local hardware stores. A century-long development of fuel infrastructure was triggered.

3

## Breaking paradigms – watch the fringes

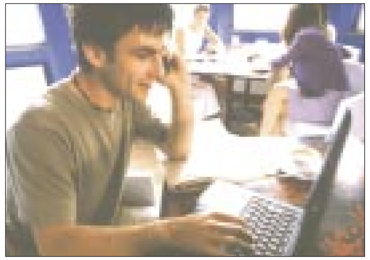
Those who make automobiles know that fuel cell vehicles fit the mood of the day because they are cleaner, quieter and offer high performance. They can also incorporate more electrical services – digital communications, pre-entry heating and cooling, and in-car entertainment – which consumers want but which require too much power for many traditional engines.

The constraint is fuel infrastructure. Automotive manufacturers prefer methanol or direct hydrogen for fuel cells, but the fuel industry does not want to be associated with the potential health risks. From an oil industry perspective the low return is not worth the costs and commercial risks.

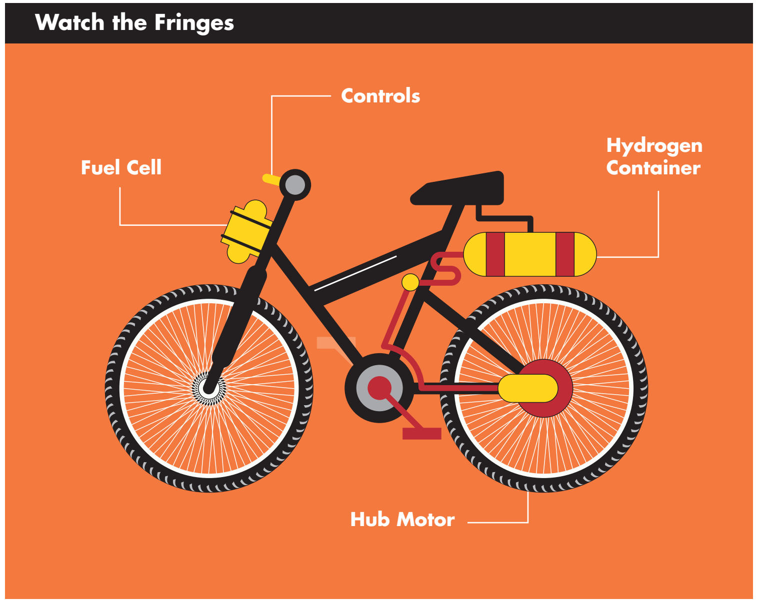




The Sony Walkman broke the paradigm that music had to come from a source plugged into a wall. Focus groups repeatedly dismissed the idea. Portability quickly spread to phones and computers



Technology innovations often come from niche market fringes, where physical constraints force innovation and consumers are willing to pay a premium. Incumbent suppliers often ignore these small markets.



The auto industry breaks this dependence by developing a new 'fuel in a box' for fuel cell vehicles, building off advances emerging from small scale applications in fuel cell powered bicycles, computers and cell phones. A six-pack of fuel (12 litres) is sufficient for 400 km. Fuel boxes can be distributed like soft drinks through multiple distribution channels, even dispensing machines. Consumers can get their fuel anywhere and anytime.

Like the Sony Walkman 20 years before, fuel in a box breaks distribution paradigms. The fuel itself is made from oil, natural gas or biomass. Sealing it in a box overcomes health concerns. Customers do not know what is inside – as far as they are concerned it could be water, which is what comes out of the end of the fuel-cell vehicle.

> **"The internal combustion engine will go the way of the horse. It will be a curiosity to my grandchildren"**
>
> *Geoffrey Ballard, founder of Ballard Fuel Cells*

The boxed fuel is sold through established distribution channels or delivered directly to consumers. Hypermarkets are happy to sell an attractive new product commanding a premium. It is particularly acceptable in developing countries with limited fuel infrastructure and constraints on urban space.

### One size fits all

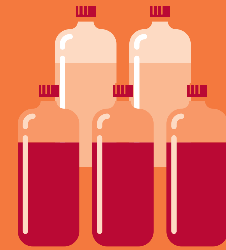
Fuel cell sales start with stationary applications to businesses willing to pay a premium to ensure highly reliable power without voltage fluctuations or outages. This demand helps drive fuel cell system costs below $500 per kW, providing a platform for transport uses and stimulating further cost reductions. To meet tough automotive standards, fuel cell system costs are driven well below the cost of capacity from conventional power and heat technologies. Suppliers of home appliances become major manufacturers and distributors of stationary fuel cells to compensate for saturated OECD markets for their existing products. Commercial and residential buildings take advantage of these low-cost fuel cells, and established natural gas grids, to produce and trade surplus peak-time electricity through internet markets. Hot water is provided by surplus fuel cell heat.



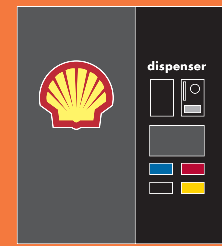
When size or weight thresholds are crossed, new distribution options open up. Fuel could be repackaged in containers the size of large drink bottles and sold through a range of new distribution channels.

**New Options for Fuel**

**What options would 12 litres of fuel for 400 kilometres create?**

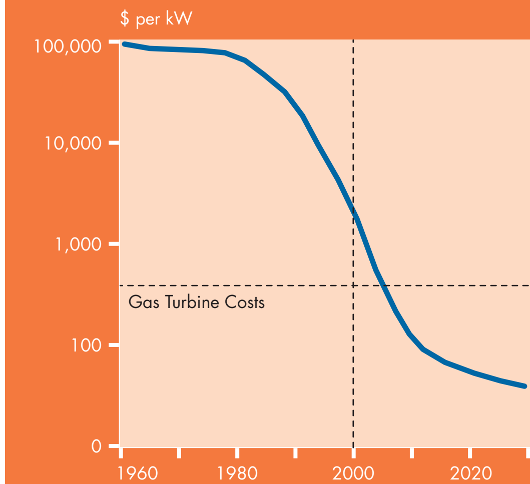


**Freedom with...**




After extraordinary cost reductions for PEM fuel cells over the past decade, manufacturing scale brings costs below $500 per kW by 2006 and $50 per kW shortly after 2010, to be directly competitive with internal combustion engines.

**PEM Fuel Cell**
System Costs



Fuel cell cars can also be used with 'docking stations' to provide energy to homes and buildings. The US vehicle fleet, with more installed power capacity than the current global electricity industry, is put to better use.

**Web-enabled control and service systems make it possible to monitor and maintain microgrids remotely**

*Göran Lindahl, ABB CEO announcing divestment of its large-scale traditional power business.*

Fuel cells and boxed fuels are perfect for rural needs in emerging economies, where many consumers can only afford small amounts of fuel at one time. They replace LPG bottles, kerosene and traditional lamps and cookers. Where power supplies are unreliable, companies prefer low-cost self-generation. In many African countries, where most industries already have backup generation, trucks are able to double as power sources.

### Technology convergence

By 2025 a quarter of the OECD vehicle fleet already use fuel cells. They account for half of new OECD vehicles and a quarter of worldwide sales. Less than a 5% increase in gas production is sufficient to meet fuel demands. The global automobile industry rapidly consolidates around the new platform.

Technical advances in transport and power services feed off each other, solving mutual problems. Fuel cells and hydrogen electrolysis are mirror images of the same technology. All benefit from broader advances in materials technology. Carbon nano-tubes are widely used by 2025 because of their superior strength, supporting the development of carbon nano-fibres as the ultimate hydrogen storage medium. But this storage is not essential and the eventual transition from liquid fuels to 'solid' hydrogen is largely unnoticed.

### Chinese leapfrog

By 2025 China – with huge and growing vehicle use – faces an unacceptable dependence on oil imports. Unease about the sustainability of regional gas resources and fears about the reliability of external gas suppliers push towards the use of indigenous coal. But this is becoming





### Many routes to hydrogen vehicles

**Boxed fuels are only one of several potential ways of delivering hydrogen to vehicles. Hydrogen can be produced by hydrocarbon reforming, nuclear or solar electrolysis and biomass conversion. Natural gas steam reforming is by far the cheapest currently, even if carbon dioxide sequestration is required. The most efficient and effective way of distributing the hydrogen is through the existing liquids and gas infrastructure, producing hydrogen at retail sites or on-board vehicles. The critical issue is how to store it.**
**There are four options:**

***Solid hydrogen*, if commercialised, would provide superior convenience, safety and – possibly – cost. Breakthroughs could come anytime but most observers suggest they are at least a decade away.**

***Liquid hydrogen* has generally been rejected as impractical and uneconomic because of concerns about boil-off, filling and safety.**

***Gaseous hydrogen* is already used for bus fleets and could fuel ultra-efficient cars with redesigned fuel tanks. Hydrogen could be produced at retail sites by natural gas reforming, supporting parallel developments in stationary markets. There are concerns over filling, convenience, safety and consumer interest.**

***On board reforming* of hydrocarbon liquids is preferred by automakers because of fuelling and space considerations, despite losing most efficiency benefits over advanced internal combustion. Methanol is easier to reform than oil but there are concerns about toxicity and the need to build new infrastructure for a transition fuel. Oil is easier to distribute, but faces performance and cost challenges and would require a cleaner fuel.**

**Cost is unlikely to be the determining factor. The winner will be determined by the strength of consumer interest in fuel cell vehicles, weighed against the convenience of competing options.**

logistically and environmentally problematic. Land scarcity limits bio-fuel opportunities. India faces similar problems.

Meanwhile the growing global demand for gas and hydrogen is supported by – and spurs – advances in low cost and unobtrusive in-situ extraction of methane and hydrogen from coal and oil shales. Carbon dioxide sequestration is feasible and enhances productivity. These advanced hydrocarbon developments build on established infrastructure and technologies, as well as on the cash flow and resources of existing fuel suppliers. China is able to make use of these, as well as indigenous technologies, to extract methane and hydrogen directly from its coal resources, allowing it to move energy by pipeline rather than thousands of trains.

Once fuel cells take off in OECD countries, China starts to develop a transport and power system around cost effective fuel cells fuelled by indigenous methane and hydrogen.

**Oil is not needed**

The advantages offered by the new technology push the transition to hydrogen well before oil becomes scarce. The higher the demand for fuel cells, the less people will pay for oil. As a result, oil is cheap enough to be preferred for heat and power in some developing countries but this expansion does not compensate for the declining transport market.

Renewable energy makes steady but unspectacular progress until 2025. 'Green energy' niches reach 5% in some regions but less than 1% in most others. Sales of photovoltaics to rural communities in developing countries initially grow fast. Many rural households are willing to pay a large premium for the convenience of photovoltaics and to be connected to the outside world by television. But needs soon exceed what photovoltaics can offer and there is a switch to fuel cells. As people move to cities rural energy demand further diminishes.





## A Chinese Leapfrog

China is able to exploit commercial fuel cells and advanced technologies to extract methane from indigenous coal resources in order to develop a fuel-cell based energy system supported by a methane/hydrogen distribution grid.

3

Government support helps renewables early in the century but price prevents them from replacing existing sources, particularly in markets like Europe with excess power capacity. Competition drives down electricity prices and although renewables continue to increase their competitiveness, they cannot close the gap. Renewable energy is also largely perceived as yesterday's technology with few obvious advantages for consumers.

### A new infrastructure

After 2025 the growing use of fuel cells as a heat and power source creates a rapidly expanding demand for hydrogen. It is widely produced from coal, oil and gas fields, with carbon dioxide extracted and sequestered cheaply at source. From 0.3 billion tonnes carbon in 2025 sequestration reaches 2.3 billion tonnes per annum by 2050, a fifth of emissions. This is still a small share of the potential sequestration capacity. But shortly after 2050 carbon dioxide sequestration peaks.

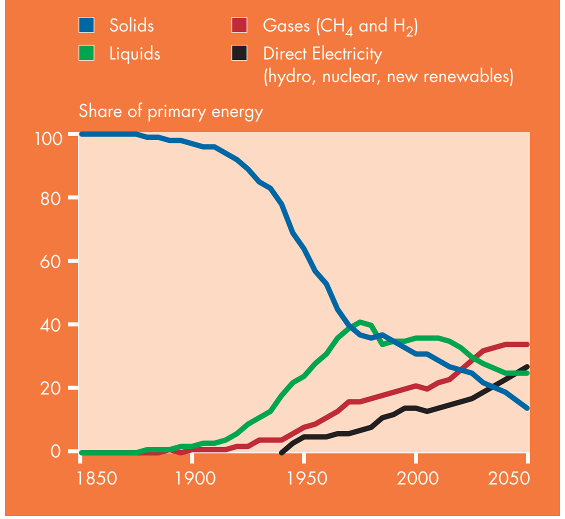
Large-scale renewable and nuclear energy schemes to produce hydrogen by electrolysis become attractive by 2030. Renewable energy becomes a bulk supply business and starts to expand rapidly.

Hydrogen is transported in gas grids until demand justifies dedicated hydrogen pipelines. A century-long process of hydrogen infrastructure development begins.



Energy supplies continue to evolve from solids through liquids to gas (first methane then hydrogen), supplemented by direct electricity from renewables and nuclear and long-term sources of hydrogen gas.

***Spirit of the Coming Age***
Evolving Energy Forms

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In *The Spirit of the Coming Age* the impact of a major discontinuity in energy technology is highlighted. The driver is a superior end-use technology pulled by consumers, which remakes the energy system around it.

The key point is the potential for new technologies to emerge from unexpected parts of the energy system. An indirect path toward renewable energy is followed, with advanced hydrocarbon technologies providing a bridge to a hydrogen economy in countries like China and India, and eventually creating a large demand for renewables and nuclear. On the surface this world appears chaotic because of the disruptive new technology. The early period is one of wide experimentation, with the eventual winners hard to see. But underneath a new infrastructure logic is emerging, although this only becomes clear after several decades.





**Timeline** ***Spirit of the Coming Age***

**2005** First stationary and vehicular fuel cells - high consumer interest

**2010** Gas resource outlook expands
Fuel cell fuel distribution innovations
Renewables limited to niches

**2015** Convergence around fuel cells for transport and stationary uses - gas network backbone

**2020** Unconventional oil & gas expand in China and India
Fuel cells reach 25% of sales in OECD

**2030** Solid $H_2$ Storage transition
Renewables pulled by strong $H_2$ demand

**2040** $H_2$ infrastructure expansion

## Conclusion

These two scenarios explore different paths to a sustainable energy system. At some point, beyond 2050, the elements that underlie the two paths could converge, possibly with hydrogen as the preferred energy carrier and storage medium. But over the next two to three decades technology, economics and social and personal choice will determine the direction.

The scenarios have five common features:
1) the important role of natural gas as a bridge fuel over at least the next two decades and the importance of reducing supply security fears,
2) the disruptions which oil markets will face as new vehicle technologies diffuse,
3) the shift towards distributed or decentralised heat and power supply for economic and social reasons,
4) the potential for renewables to be the eventual primary source of energy and the importance of robust energy storage solutions, and
5) the difficulty of identifying winning services or technologies in a period of high innovation and experimentation.

The key differences between the two scenarios, and their dominant energy products, reflect different energy resource potentials, the timing and nature of technology possibilities and social and personal priorities – in such areas as: health, security, the environment, convenience, aesthetics and the openness to change.

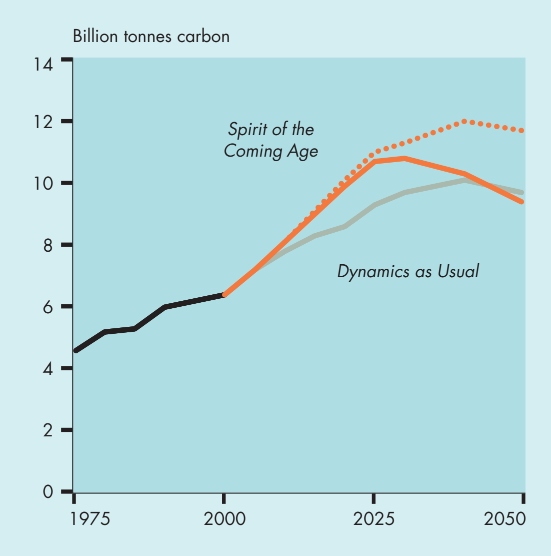
The scenarios have explored possible paths towards an affordable, sustainable energy system which has found solutions to environmental concerns, including stabilising atmospheric carbon dioxide concentrations below 550 ppmv. The scenarios suggest that by 2050 such a system could be clearly visible and rapidly emerging. The energy system will also have been through its toughest test – meeting the huge energy needs of the vast majority of the world's population as they pass through industrialisation and seek to improve the quality of their lives.





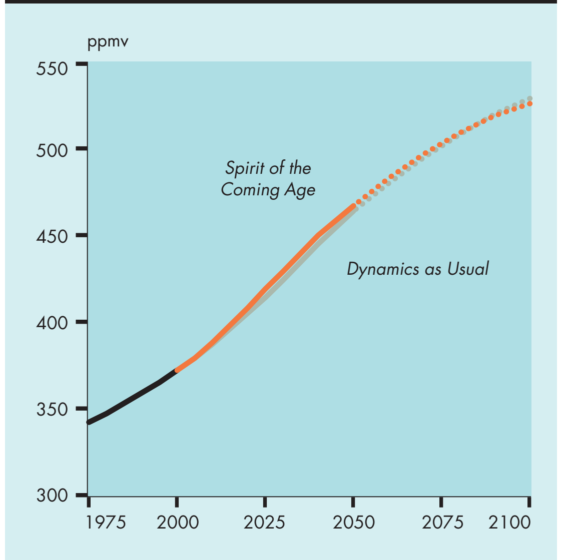
In both scenarios carbon dioxide emissions turn down by 2040.

### $CO_2$ Emissions




Atmospheric concentrations remain below 550 ppmv until the end of the century and appear on track to stabilise below this level.

### $CO_2$ Atmospheric Concentration



## Summary quantification (exajoules)*

| | 1975 | 2000 | 2025 | 2050 | 1975-2000 | 2000-2025 | 2025-2050 |
|---|---|---|---|---|---|---|---|
| Population (billion) | 4 | 6 | 8 | 9 | 1.5% | 1.0% | 0.6% |
| GDP (trillion 2000 $ PPP) | 23 | 49 | 108 | 196 | 3.1% | 3.2% | 2.4% |

| ***Dynamics as Usual*** | 1975 | 2000 | 2025 | 2050 | 1975-2000 | 2000-2025 | 2025-2050 |
|---|---|---|---|---|---|---|---|
| Primary Energy | 256 | 407 | 640 | 852 | 1.9% | 1.8% | 1.2% |
| Oil | 117 | 159 | 210 | 229 | 1.2% | 1.1% | 0.3% |
| Coal | 70 | 93 | 128 | 118 | 1.1% | 1.3% | -0.3% |
| Coal $CH_4/H_2$ | 0 | 0 | 4 | 16 | - | - | 5.8% |
| Natural Gas | 47 | 93 | 167 | 177 | 2.7% | 2.4% | 0.2% |
| Nuclear | 4 | 29 | 35 | 32 | 8.1% | 0.8% | -0.4% |
| Hydro | 17 | 30 | 41 | 39 | 2.4% | 1.3% | -0.3% |
| Biofuels | 0 | 0 | 5 | 52 | - | 10.2% | 10.1% |
| Other Renewables | 0 | 4 | 50 | 191 | 8.7% | 11.2% | 5.5% |

| ***Spirit of the Coming Age*** | 1975 | 2000 | 2025 | 2050 | 1975-2000 | 2000-2025 | 2025-2050 |
|---|---|---|---|---|---|---|---|
| Primary Energy | 256 | 407 | 750 | 1121 | 1.9% | 2.5% | 1.6% |
| Oil | 117 | 159 | 233 | 185 | 1.2% | 1.6% | -0.9% |
| Coal | 70 | 93 | 150 | 119 | 1.1% | 1.9% | -0.9% |
| Coal $CH_4/H_2$ | 0 | 0 | 6 | 97 | - | - | 11.6% |
| Natural Gas | 47 | 93 | 220 | 300 | 2.7% | 3.5% | 1.3% |
| Nuclear | 4 | 29 | 46 | 84 | 8.1% | 1.9% | 2.4% |
| Hydro | 17 | 30 | 49 | 64 | 2.4% | 2.0% | 1.1% |
| Biofuels | 0 | 0 | 7 | 108 | - | 11.8% | 11.8% |
| Other Renewables | 0 | 4 | 38 | 164 | 8.7% | 9.9% | 6.0% |

** Nuclear, hydro, wind, solar and wave expressed as thermal equivalents*

## Glossary

| | | |
|---|---|---|
| **1 Gigajoule (GJ)** | = | 0.17 boe |
| | = | 0.027 mcm gas |
| | = | 0.04 mt coal |
| | = | 0.28 MWh |
| **1 Exajoule (EJ)** | = | $10^9$ GJ |
| **1 tonne (mt)** | = | metric ton |
| **1 barrel oil equivalent (boe)** | = | 5.8 GJ |
| **1 tonne oil equivalent (toe)** | = | 42.7 GJ |
| **1 million cubic metres gas** | = | 37 GJ |
| **1 million tonnes coal** | = | 25 GJ |
| **1 MWh** | = | 3.6 GJ |
| **ppmv** | = | parts per million volume |