Future Science

Energy for Australia in the 21st Century: The central role of electricity

Affordable, secure, sustainable

Australian Academy of Science

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Foreword

The Australian Academy of Science is proud to have had the opportunity to partner with the Defence Science and Technology Group to produce a series of science foresighting reports examining likely medium-term developments and advances, in a range of enabling, cross-disciplinary fields of science. These reports offer insights into emerging science and technology applications and provide guidance on how Australia can better position itself to reap the economic and social benefits on offer.

These reports would not be possible without the expertise of Academy Fellows and other leading scientists who form Expert Working Groups to review the current literature and emerging scientific directions, and collate them in these reports in a way that is accessible to an informed, general audience. In this way, these reports are consistent with the Academy's mission of promoting scientific understanding.

Electricity generation and distribution have been fundamental to Australia's economic and social progress for over a century. However, while there has been an ongoing and rapid evolution in the way we use electricity, the supporting infrastructure of large-scale electricity generation and distribution has remained largely unchanged, in type if not in scale.

This report, *Energy for Australia in the 21st Century,* examines the science and technology that will both drive and enable a transformation in Australia's electricity system over the coming decades. It does so by focusing on three key drivers of affordability, security and sustainability that together demand a future energy system which has the flexibility to meet short, medium and longer-term changes in supply and demand.

The challenge of achieving this will not be trivial—it has been likened to that of achieving a wholesale upgrade of air transport infrastructure without interruption of flight schedules—and will require a coordinated and long-term strategic approach from government and industry.

Most importantly, the challenges to be overcome will require the very best of fundamental science and resulting technological developments to ensure Australia's future prosperity in an increasingly electricity-dependent world.

The Academy is very appreciative of the contributions made to this report by the Working Group members and other experts. The Academy also thanks the Defence Science and Technology Group for providing financial support to prepare this document.

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1 Executive summary

As in nations the world over, the operation of the Australian economy and the smooth working of its society depend in very large measure on the supply and distribution of energy for domestic, commercial, industrial, public and transportation use.

Of particular importance is Australia's capacity to generate, distribute, store and utilise electricity, since its use and usefulness is increasing and diversifying. Industrial machinery is usually electrically powered, as are urban train and tramway systems. Almost all lighting—domestic, commercial, industrial and public—relies on electricity, as do households. The information and communications technology revolution that has so influenced every aspect of our lives depends on a reliable supply of electricity. Over coming decades we can anticipate that electrically-powered cars will increasingly displace those using fossil fuels.

Australia's current system of electricity generation, distribution and utilisation has developed over many decades and carries the hallmarks of its origins and evolution. More than 80% of Australia's electricity is generated by large power plants located close to their sources of fuel: coal mines or hydroelectric dams. Significant environmental challenges accompany these forms of electricity generation. Generally, the source of the power is distant from the major end-use markets in the capital cities, which means substantial networks of high-voltage power lines (the 'grid') are needed to bring the electricity to where it is consumed. This gives rise to inevitable losses during transmission, with losses also occurring in the low voltage sections of the grid which brings the power to users.

Given that Australia's capacity to store electricity is currently limited, virtually all electricity is generated for immediate use. Balancing supply and demand, often on a minute-by-minute or even second-by-second basis, is a major challenge for grid operators. The growing use of renewables such as solar and wind energy—which are inherently variable—adds to these difficulties.

However well the existing system has served Australia in the past, it will be inadequate to see us through the current century. It must be substantially reshaped and redirected if we are to maintain our current (and anticipated) standard of living and quality of life, and create new work patterns and opportunities. In this vital task Australia currently appears to be behind many other comparable nations.

What is required?

The redesign and redeployment of Australia's electricity infrastructure must take into account three vital and interacting requirements.

Firstly, electricity must be **affordable.** Given the vital role played by electricity in every aspect of Australia's society and economy, the cost of electricity must be kept as low as possible and within the reach of all.

Secondly, the electricity supply must be **secure**, that is, reliable and resilient. The consequences of any breakdown of the electricity flow are severe, be it from resource constraints, generator breakdowns or cuts to the grid. The current strategy for increasing reliability is to build major overcapacity in both generation and distribution, so that 'peak demand' can be met—even if it occurs for only a few dozen hours a year. Such over-engineering adds significantly to costs. Diversification, decentralisation and demand management are key tools which need to be explored in future.

Thirdly, electricity generation and delivery must be **sustainable** in terms of fuel supply and environmental impacts. The fuel source for most power generation has traditionally been fossil fuels, which have finite availability at acceptable cost. Opportunities to expand hydropower resources are limited by geography and topography, and Australia has already developed much of its economically-feasible hydroelectric resources. Sustainability also involves the minimisation of environmental impacts, the most important of which is the threat to the stability of our climate arising from the growing atmospheric load of 'greenhouse' gases released predominantly by the burning of fossil fuels. However, other environmental concerns, with socio-political overtones, must also be faced, such as the visual impact of wind turbines, or the impacts of large-scale open-cut coal mining or coal seam methane extraction on agricultural production and water supply.

If Australia is to design and implement a future electricity 'ecosystem' that is affordable, secure and sustainable, it faces many challenges. The solutions to these challenges will be strongly influenced by developments in science and technology. Substantial public and private investment in research, development and demonstration will be needed if Australia is to achieve four significant objectives:

» To diversify its range of electricity sources, lower their costs and limit their environmental consequences
» To secure the many benefits that flow from an enhanced capacity to store electricity
» To enable greater benefit from electricity use through implementation of smarter distribution grids and higher end-use efficiencies
» To provide a range of new and diverse energy industries and employment opportunities.

Consideration of the technological options, developments and challenges facing Australia as it works towards these four objectives lie at the heart of this report. Achieving these advances will require new developments in materials, components and systems, many of which are on the horizon, others of which will require significant additional research. That research must be guided by a strategic understanding of future energy needs and the most productive ways to meet them.

What are the challenges?

Designing and implementing an electricity ecosystem able to meet Australia's needs through the coming century will require significant innovation in three main areas, each heavily reliant on advances in electrical energy science and technology.

Sources. To reduce the current high dependence on large, centralised coal-fired power stations, with some input from hydroelectricity and gas, Australia must plan to broaden its base of electricity generation through new sources which have emerged and which continue to emerge from research and development. Australia has significant competitive advantage in many of these alternative sources, either in access to relevant resources (for instance, solar, wind and geothermal) or in substantial technical expertise, and in some cases in both. A clear finding of this report is that the mix of power sources that will make up Australia's future electricity infrastructure will be determined by resource availability and distribution, environmental considerations and economic factors.

Storage. Australia's future electricity ecosystem will require a substantial capacity to store electrical energy and to release it for use as needed. Such storage capacity will enable maximum use of variable flows of electricity from renewable sources like solar and wind. It will enable 'time shifting', allowing the generation and storage of electricity at times of low demand and low cost, making such power available when demand and cost is higher. In this way, the need to cater for 'peak demand', which currently requires costly but rarely-used duplication of generation and transmission infrastructure, can be reduced, with significant cost savings. Finally, storage capacity, on the appropriate timescales, can greatly enhance the flexibility at the disposal of the operators of electricity generators to respond to rapid changes in supply and demand.

Energy storage is already in place in several locations in Australia, with the availability of pumped storage associated with hydroelectric schemes. Elsewhere, some facilities store energy as compressed air in underground caverns and in the rotational energy of flywheels. Cryogenic storage is showing some promise, as is superconducting magnetic storage, though the latter still presents significant technical challenges. Super-capacitors are another potential storage route, one in which Australia has notable expertise.

Advanced batteries appear the most promising storage option in the near term. Their scalability and absence of moving parts makes them suitable for decentralised storage, close to the electricity producer, substations on the distribution grid, or the electricity consumer. Australia has substantial research and expertise with respect to battery technologies, particularly in redox flow battery technology and in hybrid formats which combine two or more different storage technologies. The growing popularity of electric vehicles, whether all-electric cars or hybrid vehicles which combine electric motors and petrol engines, offers the opportunity to further integrate the electricity and transport sectors. An important additional capability is the use of vehicle-based electricity storage as a distributed element of the electrical network.

End use. Substantial technical innovation is also required in the transmission and use of electrical power. Many options have been developed in recent years to enhance the efficiency with which electricity is consumed in appliances and machinery, which has effectively lowered both demand and cost. Traditional electricity grids fall well short of the efficiency and flexibility available through new generation 'smart grids'. Information and communication technologies will have to be integrated into the grid to maximise the efficiency of both generators and consumers.

What actions should Australia take?

Australian research institutions, such as the CSIRO and a number of universities, have a strong track record of research in many of the fields relevant to the new energy challenges, including in photovoltaic technology, battery storage and control systems, but overall the effort is fragmented. While some of this research is indirectly influenced by the annual priorities of research funding agencies, much is being undertaken in the absence of over-arching Australian goals, strategic directions or coordination. Past support for energy science and technology in this country has been 'stop-start', with much good work lost overseas, not pursued or abandoned as government priorities or responsible agencies changed. In addition, support for linkages to industry that provide capacity to commercialise research findings have commonly been less than optimal.

To overcome this shortcoming, this report recommends the establishment of a government-funded National Energy Research Institute to facilitate cooperative research, sharing of research infrastructure and the achievement of strategic long-term goals. Such an institute would contribute significantly to Australia's capacity to maximise new sector opportunities and ensure that benefits flow to Australia.

This report also recommends that the proposed new National Energy Research Institute provides specific support for industry R&D relevant to new energy systems. Linking R&D to commercial markets is considered vital to successful innovation in this field, as it was for the coal, gas and petroleum sectors.

Australia's institutional energy structures and associated energy policy frameworks are now a greater barrier to new technology development and uptake than technology performance or cost. Australia's national electricity market was designed in the 1990s and is struggling to respond to the rapid changes in energy technologies and end-use behaviour. To a significant extent it is the victim of 'technology lock-in': technological choices taken in previous decades are now so deeply embedded that they constitute an impediment to innovation and the implementation of new and more appropriate solutions.

Consequently, this report recommends that new energy market structures should be examined and implemented so that Australia can continue to gain maximum benefit from current and future technology changes. Institutional structures should be technologically-agnostic to provide flexibility in utilising the most appropriate new technologies as they are developed and mature.

Energy management, control and communication technologies will play a central role in developing the diverse, interconnected energy systems of the future, so this report recommends that Australia should build on its information technology, communications and electronic control expertise and work closely with strategic international partners to develop new energy system control and management platforms. This would parallel what was achieved with WiFi innovation in the telecommunications sector.

Finally, Australia has a key role to play in our region, where energy supply and cost is a key—and often limiting—factor in, economic, environmental and social development. This report recommends that Australia should place a high priority on working with our neighbours to develop new energy systems and to help solve their energy problems, since those have, inter alia, strategic security implications for Australia.

2 Introduction

The supply of energy is vital to the functioning of any modern society and economy. As with other advanced economies, most energy used in Australia has its origins in fossil fuels, with oil-based fuels powering most transportation, the burning of coal generating the bulk of our electricity and gas used by industry and households.

This report concentrates on the vital role played by electricity in our energy economy. There are a number of reasons for this emphasis. While only a quarter of our final energy usage is in the form of electricity, its versatility underpins its involvement in almost every aspect of our society and economy—be it in industry, commerce, transportation or domestic life. Technological trends such as the growing popularity of electrically-powered personal transportation and the central role played by the internet and its attendant systems, mean that an affordable, reliable flow of electricity is more important than ever.

The versatility of electricity also shows up in the diversity of methods by which it may be generated. In addition to the output of fossil-fuelled power stations, significant electricity is generated in Australia from hydroelectric sources and growing amounts from other 'renewables', particularly wind, bioenergy and solar. A major appeal of such renewables is that they are low- or zero-emission technologies in terms of the generation of greenhouse gases.

A third reason for the concentration on electricity lies in the fact that its future utilisation will be strongly influenced by science and technological developments. These will impact on the processes and systems whereby electricity is generated, the capacity to store electrical energy, the networks by which it is distributed to users and the efficiency of its end-use. Such developments appear certain to make our future electricity 'ecosystem' markedly different from that which operates today. To maximise the benefit of such changes, strategic planning is necessary and many technological and management choices must be made.

The future of Australia's electricity systems

Australia's current system of electricity sources, distribution networks and endpoint utilisation has grown up over many decades and carries the hallmarks of its origins and evolution. It is characterised by a relatively small number of large centralised generation facilities. The majority are powered by coal, and located close to sources of fuel, though smaller contributions are made by hydroelectricity, gas turbines and increasingly by wind and other renewables. Their location commonly requires long transmission lines to deliver power to the major markets in the big cities.

This system has served Australia well in the past. However, it is becoming increasingly apparent that it will be inadequate to see us through the current century. For example, Australia has experienced significant declines in average energy intensity (the proportion of energy generated that actually gets consumed), and a sustained decline in demand for electricity, although this may be reversed as new sources of demand emerge. It has also seen a rapid, indeed phenomenal, growth in the uptake of distributed energy technologies. These include on-site generation, storage, efficiency solutions and demand management technologies. Such growth has been built on a quiet revolution in materials science and electronics engineering. Australian science is playing a significant part in that revolution, with impressive contributions in solar photovoltaics, advanced batteries for storage and control systems in particular.

These developments are leading to Australia's existing, fixed electricity generation and transmission infrastructure becoming increasingly inefficient as a platform to deliver Australia's needs. In addition, while international demand for our energy resources remains high, markets are volatile and climate considerations demand that future energy systems in Australia and globally must reduce their dependency on fossil fuels.

Together, such considerations make for great uncertainty in how Australia should adapt its energy system to meet both present and future needs. Of one thing we can be certain: advances in science and technology will continue to provide new opportunities in the way we conceive of our energy system and, in so doing, challenge existing paradigms.

Australia is an advanced economy with much riding on its own energy future, so Australian science must continue to play an important role. As part of a global innovation system we should expect no less. The global energy system is experiencing an explosion of innovation opportunities. This document outlines our view of some of the recent developments where Australian science could and does play a role in shaping its own energy future, and contributing to that of the rest of the world.

The focus of this report is on new and emerging energy science and technology. That means that the backbone of the existing energy system, currently provided by fossil fuel resources, is not covered. That does not mean there is no new science in the fossil fuel area—in the so-called 'unconventionals', there clearly is. Those developments have been covered in a recent Australian Council of Learned Academies (ACOLA) report.[1]

This report largely focuses on the non-transport component of Australia's electricity future. However, since electrically-powered vehicles are now entering the market, and their number is forecast to grow, the implications of electrified transport will also be discussed.

This account is by no means complete or comprehensive. There is an emphasis on the electricity system where change is occurring fastest. However, the primary requirement is for 'systems thinking', given the increasing complexity and interconnectedness of sources and end uses. The ultimate goal is easy to articulate. Australia's electrical energy system needs to be **affordable, secure and sustainable.** The debate is over the best way to achieve these goals, and on that there is a wide range of views.

1 *Engineering energy: Unconventional gas production–a study of shale gas in Australia*, ACOLA, May 2013.

1.1 Electricity: A revolution underway

The modern age is the age of machinery. Much of it, if not most, is driven by electricity, a power source so ubiquitous in Australia that we take it for granted. The energy ecosystem that makes electricity available as an end-product to help power everyday life—both the energy technologies used today in Australia and the emerging technologies which Australia might consider—covers a vast and complex array of possibilities. Many of these are interconnected in diverse ways, making the choice of any single solution almost meaningless.

This report divides consideration of technologies and challenges into chapters on sources, storage and end use. However, systems thinking is integrated into these chapters, as challenges and new developments with respect to individual components of the energy ecosystem cannot be considered entirely in isolation. This is particularly the case for electricity, where more than $100 billion will likely be spent on investments in Australia over the next decade, and where planning will be essential to ensure that opportunities are realised rather than squandered.

The old certainties that guided long-term decisions about the generation, distribution and end use of electricity no longer apply. Disruptive forces first began appearing in the 1970s and are now having a powerful effect on the modern electricity ecosystem, leading to long-term structural change that is both necessary and desirable. Future decisions about the electricity network will need to be more strategic, and rely more on the capabilities of emerging technologies that promise to deliver more affordable, secure and sustainable energy solutions.

The old model of generating electricity—in large centralised power plants far from population centres, generating immense quantities of power in real time and for immediate use—requires much more energy to be used than is ever really needed; wastage, inefficiency and unnecessary emissions, when fossil fuels are used, are the consequence. While new types of central generation will continue to be developed, based on solar, wind, geothermal and other technologies, it will be important that transmission, distribution and end-use efficiencies be maximised to maintain cost-effective supply. From individual buildings to the precinct and urban level, insufficient thought has been given to energy efficiency, even though new materials and technologies can now make efficiencies not only possible, but can contribute to dramatic cost reductions in energy use and central infrastructure construction.

While complex systems have evolved over time to manage the burgeoning electricity ecosystem and improve its performance and reliability, new technologies are emerging which have the potential to create a new paradigm that allows for enormous productivity improvements across the system. The new paradigm—powered by information and communication technologies—facilitates greater flexibility in the location and time of generation, and focuses attention on the dramatic improvements that can be made across the network itself.

Another key driver for change is our need to reduce emissions generally, and greenhouse gas emissions in particular, in a world increasingly concerned about the impact of climate change. Electricity production stands out as not only the largest sectoral contributor of greenhouse gases in Australia, but also the one that has steadily increased globally over the last four decades. In Australia and other developed economies, electricity demand in the past few years has started to fall or plateau—an indication that a large-scale transition is already underway, although new sources of demand, such as transport, will emerge.

In addition, ageing electricity plants must be replaced over the coming decades. This could cost as much as $100 billion, thanks to the ballooning cost of new centralised generation facilities. Hence, the case for more energy to be made available for less cost (both monetary and environmental) is clear. A 'business as usual' approach to the expansion of the current infrastructure will ultimately cost more, deliver less and still fail to keep up with the changing needs of end users.

1.2 Centralised generation: An outdated paradigm?

The Australian electricity supply system has historically relied on centralised generation and continues to do so. Driven by the economies of scale and costs of transport, large generating facilities were located adjacent to fuel sources (often coal or gas) that were often relatively distant from centres of demand in populated centres. Once generated, bulk electricity would be sent over a traditional grid to distribution centres and eventually to users, whether residential, commercial or industrial. Such an approach was driven by and relied on the relative costs of transporting fuel vs extended transmission and distribution grids.

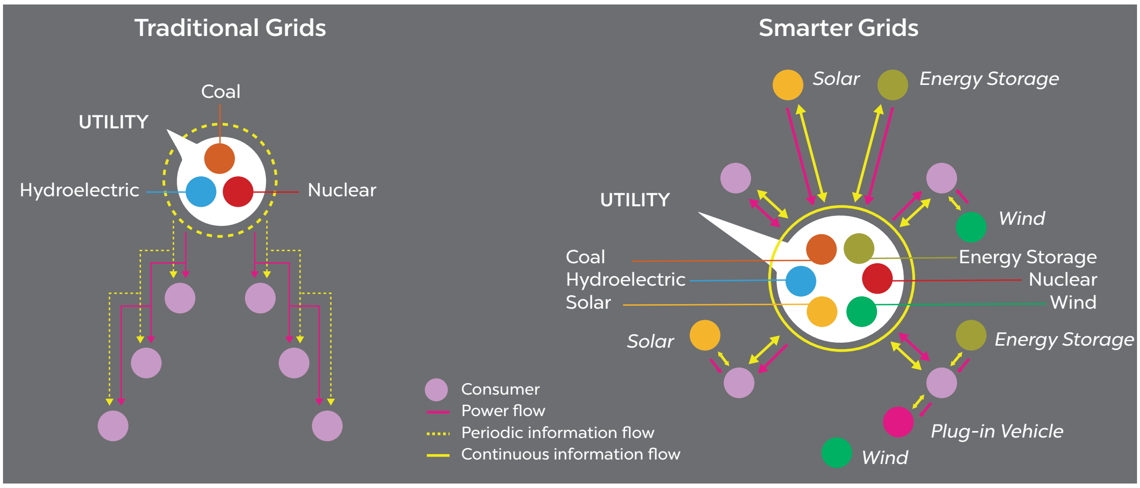

Figure 1: Comparison of traditional grids with smart energy networks. Image courtesy James Sciales, IBM Research.

Over time, however, costs of scale started to outweigh economies of scale. The scale and inter-connectedness of the grid and impact of labour costs led to relatively higher costs of the network, and the costs of generation fell relative to distribution. As the requirements of increasingly sophisticated industrial, retail and domestic equipment rose for reliable supply, more had to be invested to maintain and improve service standards.

The other shortcoming of centralised power is that not all of the power generated reaches end users; some of it is used by the stations themselves and some is lost in transmission. Of the 245 terawatt-hours (TWh)[2] of electricity generated in 2013 in Australia, about 6% (15 TWh) was used by the generators leaving 232 TW as the dispatchable production. A further 10% was lost in transmission and distribution, leaving 209 TWh for final consumption by users.[3] In the same year, 74% of electricity was produced by coal-fired power stations, 14% from natural gas (including coal-seam methane), 6% from hydroelectric plants and 6% from other renewables such as solar photovoltaics and wind. It is worth noting that, although electricity is responsible for 44% of Australia's primary energy production, it only accounts for 24% of final energy consumption. This is because Australia also 'exports' a significant amount of electricity 'embedded' in products such as aluminium.

The future grid is likely to have a more balanced mix of central and distributed generation, coupled to a much more diverse mix of 'supply' side and 'demand' side solutions to match energy needs to the best available energy sources.

1.3 Forces transforming the electricity ecosystem

Four main forces are driving a transformation in the vast electrical infrastructure underpinning today's economy.

» **Efficiency:** Electricity demand, both per capita and in total, has recently been falling in Australia—despite increases in population and a growing economy. This is partly the result of efficiency gains at the end-user level, ranging from more efficient buildings and industrial processes to more efficient appliances. Mandatory efficiency measures introduced in the late 1990s, such as performance standards for appliances and equipment, are estimated to have reduced annual demand for electricity by 28% between 2006 and 2013. Research in this area, especially in construction and materials, is set to drive this down further, with significant implications for the amount of energy needed to be generated, distributed and stored.

» **Energy supply:** The energy supply mix is changing due to the rise of distributed energy solutions such as photovoltaic solar panels and solar water heaters, and to the advent of new large-scale renewable generators such as solar thermal plants and

2 A terawatt-hour is equal to a sustained power of about 114 megawatts for one year. A megawatt is 1 million watts: the amount of energy used to run a large server farm or data centre, or a large commercial building.

3 *Australia's electricity*, World Nuclear Association, March 2015.

wind turbines. Distributed generators can be mass-produced, miniaturised and installed close to their loads. They are smaller, with capacities of 10 MW or less—allowing (often modular) generation capacity to be added incrementally as needed. End users are also having a growing impact, installing solar panels and becoming both producers and consumers of electricity, in turn requiring the grid to become more flexible. The cost of distributed energy systems has also fallen drastically: photovoltaic solar modules, for example, has fallen two orders of magnitude in the last 35 years.[4]

- **Storage:** There is a growing need for storage technologies (i.e. pumped hydro, flywheels, batteries, thermal storage in buildings and in solar thermal plants) to facilitate better matching of supply and demand in the grid. Storage can improve stability and efficiencies across the existing grid (e.g. frequency regulation, voltage support, smoothing out variable supply); provide greater flexibility to increase inherently-variable renewable energy generation in the future; and give users greater choice in meeting an increasing portion of their own energy needs.
- **Distribution and control:** The centralised, 'top-down' electricity network is slowly transforming into a 'smart energy network' (see Figure 1). Such a network communicates back and forth between users and producers through technologies such as sensors, computer systems, smart meters and integrated communication systems. These technologies allow utilities and end users to precisely manage electrical power demand and to switch vast numbers of small-scale distributed energy generation and storage devices in and out of the grid as needed.

Modernising the grid has become an urgent issue of national importance, driven by changes to both supply and demand side factors. On the demand side, energy efficiency programs have successfully reduced electricity demand in cities despite our growing population, and consumers are demanding supply choices that have not been demanded before (coupled with public opinion gradually shifting against coal). Reliance on telecommunications and the internet means a heightened demand for continuous electricity supply, with obvious economic implications of supply failures.

The supply side is being forced to meet these evolving expectations while adjusting to increased costs and reduced revenues, which it simply cannot achieve without embracing new technologies such as distributed generation and storage, and modernising grid control systems.

Some commentators have observed that the forces of decentralisation acting on the power industry are similar to those which have transformed information and communication technologies since the 1980s. US economist Jeremy Rifkin argues, "The same design principles and smart technologies that made possible the internet, and vast distributed global communication networks, will be used to reconfigure the world's power grids so that people can produce renewable energy and share it peer-to-peer, just like they now produce and share information, creating a new, decentralised form of energy use."[5]

This massive transformation of our electricity delivery system must be achieved without major disruption to our everyday lives and our economy which depend so much on it. The magnitude of this challenge cannot be overestimated. One commentator likened it "to the task of replacing all the aircraft, airports and traffic control systems underpinning global aviation while at the same time keeping all the passengers in the air."[6]

In the face of the enormous changes under way, Australia cannot continue to pursue an incremental, piecemeal evolution and expansion of the fossil-fuel-based centralised electrical grid, the paradigm that has largely guided policy thinking for the past century. Attention needs to be paid to long-term planning based on the best available technologies and emerging technological opportunities which can take advantage of local conditions and available natural and infrastructure assets.

Australia is not the only nation facing such enormous challenges. The United States Department of Energy has pronounced the US electricity grid "ageing, inefficient, congested, and incapable of meeting the future energy needs of the information economy without significant operational changes and substantial public-private capital investment over the next several decades." In the US, it has been forecast US$1.5 trillion worth of infrastructure investment will be required by 2030, and that transmission

4 *Quadrennial energy review,* US Department of Energy, April 2015.

5 Rifkin, J 2011 *The third industrial revolution: How lateral power is transforming energy, the economy, and the world.* Palgrave MacMillan.

6 Fox-Penner, P 2013 *Smart power,* Island Press.

and distribution infrastructure will account for more than half of that.[7]

In the decades ahead, Australia will spend many billions of dollars upgrading and expanding our electricity ecosystem, and will need new energy infrastructure. Coordinated strategies at national, state and regional levels must be developed to guide investment in technologies and to facilitate innovation and entrepreneurship. Only through long-term strategies that leverage new and emerging technologies will benefits to consumers, industry and the economy be maximised.

1.4 Affordable, secure, sustainable

The rise of new energy technologies—underway for decades but now gathering pace—is disrupting existing paradigms in both the electricity sector and the wider energy sector. These transformational changes are challenging governments, policy makers and regulators worldwide. How Australia navigates the complex and evolving world of energy policy in this sector will be greatly influenced by emerging developments in science and technology. The guiding principle of this report in considering Australia's options over the next 20 to 30 years is the need to make the electrical energy ecosystem more **affordable, secure and sustainable**.

Affordable. The present global energy system has been built on a backbone of fossil fuels. Their abundant, widely distributed nature—especially coal—has provided cheap electricity for much of the world's population, while oil has largely powered global transport systems. However, the world's stockpiles of readily accessible fossil fuels are steadily depleting and are set to become increasingly costly. In addition, more than a billion people in the developing world live without electricity and the cost of importing oil is a significant burden on many economies.

Emerging technologies offer a plethora of options—especially in distributed energy, storage and efficiency gains—with the potential to provide affordable energy services to many more people, whether in cities or remote locations, at lower economic and environmental cost. Our ability to harness low-emission electricity in particular is increasing rapidly through remarkable technological advances, particularly in renewables, and the cost of doing so is declining.

Secure. In the developed world, we have become accustomed to reliable, on-demand electricity services. However the security and stability of our electricity supply is a growing issue. With existing dated electrical power grids built around centralised, large-scale fossil fuels (and in other jurisdictions, nuclear generation), some fear that distributed technologies and intermittent renewables cannot be incorporated without jeopardising the stability of the grid. In reality, the addition of renewable energy sources, distributed energy and storage technologies will themselves improve security by diversifying supply and demand sources, locations and strategies.

Sustainable. All energy supply comes at some environmental cost, making demands on resources and the global environment. While the challenge of addressing environmental impacts of energy services is not new, the need to address climate change has brought the environmental impact of energy—and particularly electricity—into sharp focus. There is urgent need to manage the carbon emissions from fossil fuel use in ways that limit future climate change, and to develop energy technologies that are not carbon based.

Each nation has its own particular challenges and opportunities. Australia has a unique mix of abundant resources in the form of both conventional and unconventional fossil and nuclear fuels and renewable energy resources. Australia also has a long and celebrated tradition in energy science and technology delivery. The challenge for our policy makers is to allow the opportunities for new ways of providing energy services to emerge as best befits our national resources, skills and requirements. Such new infrastructure and systems must be characterised by flexibility, allowing advantage to be taken of options as they emerge from research and development, while avoiding 'technology lock-in'; it is not possible to predict with certainty what technologies will become dominant. It follows that planning for the future must be informed by an understanding of the possibilities of new energy science.

7 *Quadrennial energy review*, US Department of Energy, April 2015.

1.5 The importance of materials

Materials science and technology will play a fundamental role in our energy future, catalysing new opportunities to minimise energy usage, maximise storage capacity and optimise energy harvesting.

During the present century, some of the key resources that have powered global economic growth and development will either be significantly depleted, become much more expensive to extract, or be limited in use because of their cumulative environmental impacts. The benefits or services those resources provide will need to be replaced—and this will drive the emergence of new technologies that will, in turn, transform the nature of resource demand.

We are already witnessing the beginnings of this transformation in the area of low-emission energy technologies. These are underpinned by a new and different set of commodities such as lithium, indium and neodymium that empower technologies with the potential to reduce the need for more traditional resources, such as fossil fuels.

For solar photovoltaics, compounds based on indium, germanium and gallium offer potential for high efficiencies. Lithium and vanadium are key resources in battery technologies—and even the existing NiMH (nickel–metal hydride) batteries use lanthanum. Platinum and ruthenium are superb catalysts for fuel cells, and essential to many high-tech applications. Cobalt is used in lithium–ion batteries and in magnets.

Some key research challenges must be met in order to deliver these commodities more readily and cheaply to market. The first relates to their distribution and availability; our understanding of the relevant geochemistry is far from complete. Consequently our ability to resource large-scale deployment of technologies that rely on them remains uncertain.

Many of these new commodities do not occur as primary enrichments, but rather are sourced from secondary concentrates. Indium for example is found in several minerals, but none of those are occur in concentrations suitable for mining. It is currently sourced from secondary processing of zinc and other base metal ores.

Secondly, traditional processing of some of these commodities involves hazardous materials and can result in toxic by-products, including radioactive elements such as thorium. Conventional processing in environmentally-benign settings can incur considerable costs, and there is a need to provide new, cost-effective and more benign mineral processing pathways.

Elements of particular interest are the ‘rare earths’, a group of 15 elements, ranging in atomic numbers from 57 to 71, crucial to the manufacture of many hi-tech products. Principal uses for rare earths include metallurgical applications, glass polishing compounds, glass additives, and television, lighting and X-ray intensifying phosphors. Some have key roles in the issues with which we are concerned here. Permanent magnets containing neodymium and samarium are vital to vertical axis wind turbines and hybrid cars; terbium and dysprosium are used to improve magnetic coercivity.

Despite their name, rare earth elements are relatively plentiful on the Earth; it is their *extractable* scarcity that led to the term ‘rare earth’. Their geochemical properties cause them to be highly dispersed so high grade, exploitable ore bodies are rare. The demand for these new energy-linked commodities has the potential to herald a new resource boom in which Australia is well positioned to participate. China is the ‘Saudi Arabia’ of rare earths, with 23% of all known reserves. In terms of proven rare earth resources per capita, Australia has the world’s second richest reserves, and several mines are in operation.

As will be explained, energy storage is a precondition for the widespread adoption of intermittent energy technologies and smart grids, and so forms a significant driver in materials research. A global need exists for high-density energy storage systems with low losses. Fuel cell and battery research is focused on replacements for expensive noble metal catalysts and cheaper scalable membrane technologies to replace the current nafion membranes®. The requirements for high energy and power density, low weight, long life, chemical stability and recyclability place such stringent demands that to date few candidates have been identified.

1.6 Current energy systems in Australia and emerging issues

Australia’s current energy systems are an outcome of evolving energy service needs, natural resource endowments, technology developments and changing societal priorities. For the most part they have served Australia well. However for the reasons described above they are unlikely to do so in the future. It is also arguable that our current systems are the victims of ‘technological lock-in’.

Consider coal: it has played a primary role in Australian electricity provision through its wide availability in almost all Australian states, low cost and well established technologies. It expanded from the early 20th century and supplies industry and households as both a direct fuel and through electricity generation. Similarly, hydroelectric power played an early role in electrification in Tasmania and then, from the 1960s onwards, for Victoria and New South Wales through the Snowy Mountains Scheme.

From its early deployment through town gas derived from coal, natural gas began to play a greater role in industry and residential sectors and, eventually, gas-fired electricity generation in the 1970s. Early progress was seen in those states—notably South Australia and Victoria—with major gas production established before supply infrastructure was extended to virtually all major population and industry hubs. The potential of nuclear power was explored in the 1960s and at regular intervals since, but has not progressed further to date, due both to the availability of lower cost options and to the impact of social and political considerations.

The most notable developments since the mid-1970s have been:

» the extraordinary five-fold growth in primary energy production over that time, dominantly in black coal but also considerable uranium production and, to a lesser extent, gas
» the growing role of energy exports, now around 70% of national energy production
» a focus on energy-intensive industry development in several states, based on the availability of abundant and low-cost energy
» the growing role of natural gas for domestic energy consumption and for export, with the growth of LNG (liquid natural gas) export facilities
» the establishment of the National Electricity Market (NEM) with transmission interconnections across eastern and southern Australia, and an expanding gas transmission infrastructure.

Over the past decade, key developments have been:

» the discovery and development of large coal-seam gas resources in Queensland and New South Wales
» the development of major LNG export facilities in Queensland to export this new gas resource
» growing contributions from gas-fired and renewable generation (primarily wind followed by photovoltaics) within the electricity sector, driven initially by supportive policy but also benefiting from falling technology costs and excellent renewable resources across almost all of Australia
» falling electricity demand and flattening energy demand more generally, although new sources of demand are emerging.

The future energy system is likely to be far more diverse than the current one. Major trends include:

» increasingly efficient appliances, demand management and energy service delivery; these will significantly reduce the energy resources and infrastructure that are needed for energy supply
» diversification of energy supply, with a much larger portion from renewable sources and with local resource availability dictating technology choice
» rapid uptake of distributed energy technologies such as rooftop photovoltaics, solar water heating, energy-efficient buildings, and on-site storage and appliance control (at the urban scale as well as at the building scale)
» new large-scale generation options—wind, solar thermal, geothermal and others—dominating new central generation installations
» electrified transport systems with integrated storage connecting the electricity and transport infrastructure.

At present, Australia derives slightly more than a third of its primary energy consumption from oil, another third from coal and the remainder from gas (around 24%) and renewable energy (around 6%)—primarily hydro, biomass and wind, with solar rapidly growing. Energy resources account for around 30% of the value of Australia's total commodity exports. Domestic energy costs for business and households—notably for gas and electricity distribution—have grown considerably and are now becoming expensive by international comparisons.

Australia's economy is energy intensive in comparison to our major trading partners. Our emissions intensive electricity industry, with its dependence on coal generation (around 75%), coupled with an energy-intensive industrial sector, place Australia towards to the top of per-capita greenhouse gas emissions ratings. Electricity production is not only the largest contributor of greenhouse gases, but also the one that has steadily increased over the last 35 years.

This situation is increasingly problematic given the trends identified above and further considered in the pages ahead. Energy policy is increasingly difficult and uncertain, and it is to the informed discussion of such policy issues, particularly as they affect technology choices, that this paper seeks to contribute.

2 Sources: The emerging technologies

2.1 Solar photovoltaics: Progress on many fronts

Solar photovoltaic (PV) systems convert sunlight directly into electricity using semi-conductor-based devices known as solar or photovoltaic cells. Current commercial PV modules are silicon based and convert between 15 and 20% of incoming radiation into electricity. Laboratory PV cells have reached 25% efficiency, while multi-layered 'tandem' cells have reached 40% efficiency. PV cell efficiency is important because it translates directly to electricity cost reduction.

Global overview

The Earth receives about 885 million TWh of sunlight at its surface each year, which makes solar energy the most abundant and most widely distributed energy source available. The International Energy Agency predicts that 46,000 GW of new generation capacity will be required by 2050, which is 3,500 times less than the solar influx each year.[8] Recent progress in both cost and solar collection efficiency make solar energy a likely strong contributor to humanity's new energy requirements.

Everywhere on Earth receives exactly half a year's worth of sunlight per year, but the distribution and intensity vary markedly with latitude and average cloud cover, and the variations become extreme towards the poles. In the mid- and equatorial-latitudes that house the majority of the Earth's population, solar radiation typically ranges from 1 to 7 kWh/m^2/day.

PV is the fastest growing energy technology in the world, with cumulative capacity increasing on average 49% per year in the decade 2003–2013 (ibid). The International Energy Agency (IEA) expects it to contribute 16% of global electricity by 2050. PV is intimately linked to the rapid transition towards renewable-energy-based distributed, electronically controlled energy systems.

8 *Technology roadmap: Solar photovoltaic energy.* International Energy Agency, 2014.

PV use has grown rapidly over the past few decades because of its versatility and modularity. PV can be used from mW scale in watches, calculators and other small applications, through to GW scale in full-size utility power stations. Few other energy technologies can be applied so widely. Because it has no moving parts, no noise and no emissions when in operation, PV can safely be located in urban areas, on rooftops and other structures.

Australian overview

The deployment of solar PV in Australia presents both major opportunities and major challenges. The irradiance levels of sunlight which form the basis of our solar energy resources are some of the highest in the world. Mean solar radiation levels in Australia range from 6.5–6.75 kWh/m^2/day in large parts of the Western Australian desert, to below 3.75 kWh/m^2/day in areas of Tasmania (see Figure 2).

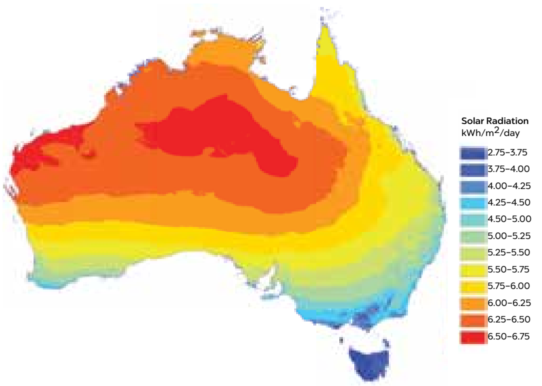

Figure 2: Australia has some of the best solar resources in the world. Image courtesy ANU Fenner School.[9,10,11]

Although Australia has world-leading PV researchers, Australia currently has no solar cell manufacturing operations and just one small module manufacturing plant. Australia does, however, have some manufacturing capability in balance of system components, including inverter technologies, micro-grid capability and control systems. The last decade has seen silicon panel manufacture shifting from Australia and other OECD countries to Asia, as manufacture has moved from a specialty to a commodity product.

The presence of solar resources and leading research may not be enough to encourage solar panel manufacturers in Australia. Current and market conditions indicate that China and the US can provide the scale and supply-chains required to support mass production,[12] and that the financial and regulatory environment in Australia has not been supportive.

Australia could benefit through commercialisation of new technologies where low cost manufacturing is employed, or for higher value 'PV-based products'. In 2014, factory-gate prices for crystalline-silicon PV modules fell below US$0.5/W and are likely to continue falling as technology and manufacturing processes continually advance, and as the industry structurally matures.[13] Such trends will continue to drive the ability to roll out PV on a larger scale, and in turn drive development of small- and large-scale storage systems and microgrids.

The PV market has only recently reached commercially viable levels and so is now set to increase rapidly without the need for government subsidies. Australia has had good experience in PV device and systems research. Even though it was not able to maintain early manufacturing opportunities, it has the potential to re-enter that market with innovative new products. PV systems research could also add value to Australia's aluminium and steel roofing manufacturers, providing a market advantage for both local use and export.

Similar advantages could be gained in other building and appliance ranges, again rejuvenating local industries which have struggled to maintain market share over recent years, or facilitating the development of new industries and new high-value manufacturing capability. Such products would require not just PV expertise and devices, but also new materials, as well as design and other expertise across the wide range of potential PV product markets. It will also link into the development and application of electronic control technologies, communication systems, electricity storage and new energy service delivery. All of these markets are potentially very large and all are on the cusp

9 Hutchinson, MF, Booth, TH, McMahon, JP and Nix, HA 1984. 'Estimating monthly mean values of daily total solar radiation for Australia', Solar Energy 32: 277–290.

10 Hutchinson, MF and Xu, T 2013. *ANUSPLIN Version 4.4 User Guide*. Fenner School of Environment and Society, The Australian National University. Available at http://fennerschool.anu.edu.au/files/anusplin44.pdf

11 Xu, T and Hutchinson, MF 2011. *ANUCLIM Version 6.1 User Guide*. Fenner School of Environment and Society, The Australian National University. Available at http://fennerschool.anu.edu.au/files/anuclim61.pdf

12 Goodrich, AC et al. 2013 'Assessing the drivers of regional trends in solar photovoltaic manufacturing', *Energy & Environmental Science* 6: 2811–2821.

13 Bazilian, M et al. 2013 'Re-considering the economics of photovoltaic power', *Renewable Energy* 53: 329–338.

of major expansion pending research outcomes and product innovation.

Markets for these will be driven less by dollars per watt and more by functionality, aesthetics, affordability and ease of deployment. The PV market in Australia is currently around 1 GW per year (see Figure 3), but given the high solar resource available, the potential market is significantly larger. With its established energy export markets, Australia is also well placed to export PV products as the world moves increasingly towards renewable energy. Nevertheless, PV development is very competitive around the world, with many countries recognising the large potential markets available. To remain competitive, Australia will need to prioritise PV systems research in addition to existing device research.

Overview of current and future technology

Crystalline silicon solar cells remain the workhorse of the current rollout of PV. Single crystal or multi-crystalline silicon wafers are connected together to form modules, typically 150–350 W each. Advances in the technology continue to improve performance and lower production costs. Technology improvement via the use of lower-quality silicon and thinner wafers, and the introduction of new technologies like hot-carrier injection and up-conversion/down-conversion (described below), are all expected to contribute to efficiency improvements and cost reduction. Australia, with key research centres at the University of NSW and the Australian National University, as well as strong research groups in CSIRO and other universities, leads the world in developing the next generation of solar cells.

All semiconductor materials have a 'bandgap' which is intrinsic to the material and defines the lowest energy light that the material can absorb. For silicon, the band-gap between the conduction and valence bands is 1.1 electronvolts (eV), equivalent to radiation in the infrared part of the electromagnetic spectrum. 'Light' with energy less than this will not be absorbed, while 'light' with energy above this will be absorbed but some of the energy will be lost. New 'third generation' solar cells aim to recover some of this lost energy by:

» generating multiple electrons for each absorbed photon ('down-conversion')

» using multiple photons below the bandgap to generate an electron ('up-conversion')

» using energy-selective electrodes to effectively increase the output voltage of the solar cell to be greater than 1.1 eV for silicon solar cells.

These are tough challenges, relying on key strengths of Australian innovation in materials science, nanotechnology and characterisation.

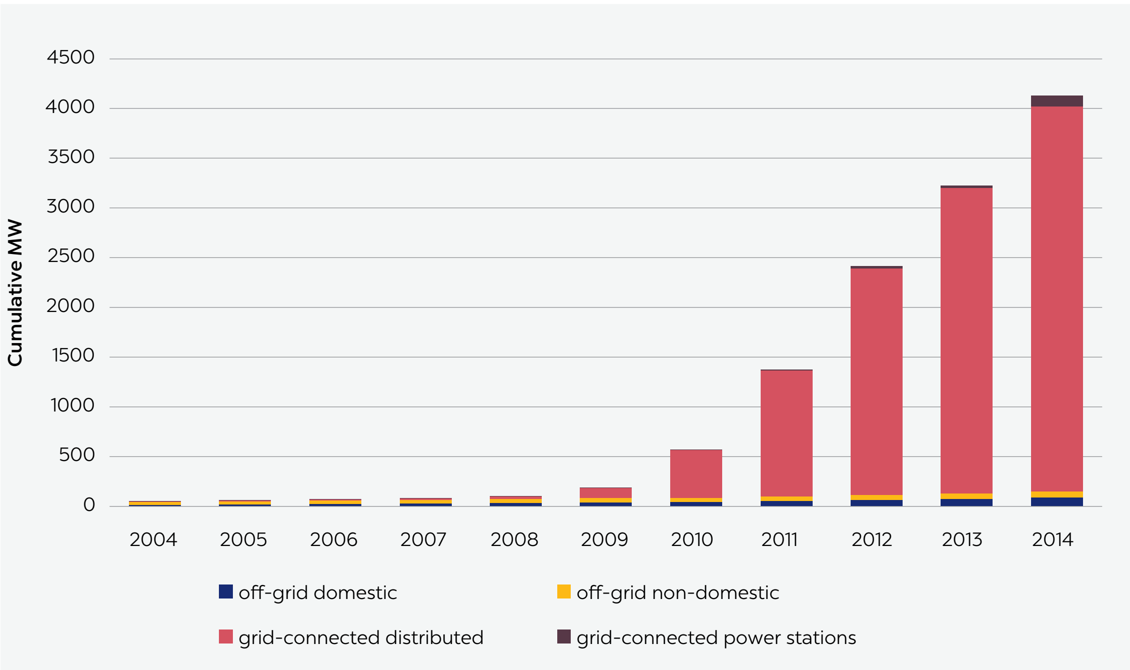

Figure 3: Development of the Australian PV Market over the past decade. Source: *PV in Australia* 2014, APVI, June 2015. Image courtesy: Muriel Watt, UNSW.

Thin-film solar cells

Crystalline silicon solar cells are relatively mature and have almost continuously improved in efficiency while reducing in cost to manufacture. It is understandable that other technologies such as thin film PVs (amorphous silicon) have struggled to gain a competitive foothold. Significant efficiency gains—or reductions in production costs—need to be made in thin-film PVs to ensure they remain competitive. Various thin-film technologies are being pursued, some of which show realistic promise.

Relatively established thin-film semiconductors include cadmium telluride (CdTe) and copper/indium/gallium/diselinide (CIGS). CdTe cells have shown promise for some years and efficiency improvements are being actively pursued, along with reductions in cost through improved doping methods. CIGS cells are improving in efficiency but some stubborn manufacturing challenges remain.

Other thin film semiconductors that are receiving commercial attention include copper/zinc/tin/sulphide, cadmium/magnesium/telluride, and various pyrites, all of which could conceivably compete with silicon-based PV cells on price if production technologies can be developed.

In a recent report, respected industry analysts NanoMarkets saw thin-film PVs as fledgling in commercial terms, with the market for the technology unlikely to reach US$120 million a year until 2021.[14] Recent financial conditions and the relentless cost reductions for conventional silicon cells have placed enormous pressure on the commercialisation of new thin-film technologies. However, in the longer term, as cost structures of current technologies stabilise, and technological hurdles are overcome for the thin-film materials, it is expected that they will find commercialisation paths as manufacturing costs are lowered.

Perovskites

Much of the research into new solar PV materials is currently centred on perovskites. This mixed organic–inorganic material, a soluble methyl-ammonium lead trihalide ($MeNH_3PbX_3$, X=I, Br), crystallises in the common perovskite crystallographic form, for which it is named.

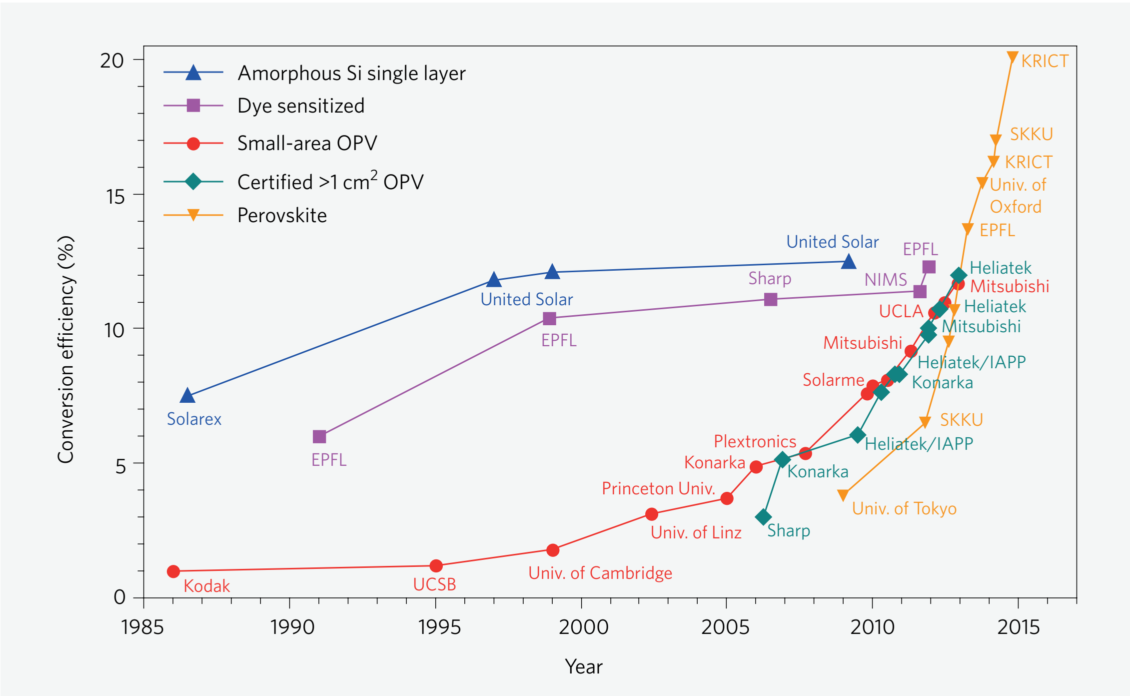

Figure 4: Development of efficiencies for several thin-film photovoltaic technologies. Perovskites have more quickly grown in efficiency than any other technology in the history of photovoltaics. Key: OPV, organic photovoltaic; EPFL, École Polytechnique Fédérale de Lausanne; IAPP, Institut für Angewandte Photophysik; KRICT, Korean Research Institute of Chemical Technology; NIMS, National Institute for Materials Science; SKKU, Sungkyunkwan University; UCLA, University of California, Los Angeles; UCSB, University of California, Santa Barbara.[15]

14 'Handicapping the field: How next-generation solar PV materials will emerge into the market', *NanoMarkets*, September 2014.

15 Adapted with permission from Macmillan Publishers Ltd. Figure 1 of Leo, K 2015 'Signs of stability', Nature Nanotechnology 10: 574–575

In recent years this technology has seen rapid efficiency improvements from 10% in 2012 to 20% in 2015, and may reach 30% before being commercially rolled out[16] (see Figure 4). The key to performance enhancement lies in understanding and controlling the crystallisation process. Future improvements are needed in material stability, replacement of lead and translation to large-scale deposition processes.

Australia is a leader in continuing research into optimisation and processing of perovskite materials. Researchers at CSIRO have demonstrated roll-to-roll printed perovskite modules as a first step in the future commercialisation of perovskite technologies. In 2015, the publicly-listed Australian company Dyesol Ltd announced scale-up programs expected to lead to commercialisation with the establishment of a prototype facility in Turkey.[17]

Despite the rapid increases in efficiency so far, perovskite PV cells will require further improvements (beyond 20% efficiency) to compete with crystalline silicon in commercial markets. However, further efficiency gains are not an unrealistic expectation within the next decade. In addition, tandem devices of perovskites with conventional silicon offer synergistic possibilities in efficiency enhancement, with the University of NSW leading a group of four universities and two companies in a $12 million development project funded by the Australian Renewable Energy Agency (ARENA).

Organic photovoltaics

Organic photovoltaic (OPV) cells are made from conductive organic polymers and have a number of properties that make them attractive as more than just competitors to conventional silicon cells. They promise cheap, lightweight, flexible, (even semi-disposable and biodegradable) solar cells that can be rapidly printed in large volumes, and could open a range of applications that have only been partially explored to date. Applications in the near-term could be in electricity-generating clothing, portable DC devices, foldable or roll-able shade covers, building- or automotive-integrated solar panels, or even evaporation covers for water storage.

Current research is delivering efficiencies of approximately 10%. In lieu of efficiency improvements in the near future, it may be possible to offset low efficiency against low material use and low cost.

OPV technologies offer the potential to significantly reduce the cost of large-scale production, with cost estimates indicating parity with conventional silicon cells is possible. Modelling indicates OPV modules could be manufactured at $7.85 ± 30% per square metre for print speeds above 50 m^2 per minute.[18]

For commercialisation to succeed on a large scale, significant improvements are needed in materials performance and durability, which will then translate to lower cost per watt. OPV cells have improved rapidly in the last few years, and remaining research challenges include improving the useful life of cells (better encapsulation), reducing the density of printing defects and developing better methods to print large-format panels. Further advances in narrow-band gap polymers would also open new applications and potentially allow tandem devices.

Australian researchers lead the world in integrated OPV materials design and characterisation, with strong printing programs, allowing excellent potential for the commercialisation and deployment of printed OPV. Know-how generated during these programs has facilitated and accelerated the development of printed perovskite materials mentioned earlier. Translation of manufacturing from wafers to printed PV is a very competitive field, and Australia's current advantage needs to be supported to ensure commercialisation paths remain in Australia.[19]

Commercial development is currently being pursued by the Victorian Organic Solar Cell Consortium (VICOSC),[20] a collaboration between academia and industry that aims to produce prototype OPV solar cells printed on plastic; and the University of Newcastle's patented Solar Paint™, a low-cost PV technology that can be printed on plastic and integrated into tinted windows.[21]

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16 'Perovskite and DSC: The market revolution begins with BIPV', *NanoMarkets*, July 2014.

17 Available at http://www.dyesol.com/posts/cat/corporate-news/post/DYESOL_SIGNS_TURKISH_HOA/

18 NanoMarkets, 2014 (op. cit).

19 'The next revolution in solar energy: high efficiency printable tandem solar cells', Clean Energy Institute, University of Washington, 2015.

20 Available at http://www.energy.unimelb.edu.au/victorian-organic-solar-cell-consortium-vicosc

21 Available at http://www.newcastleinnovationenergy.com.au/solar-paint-technology#.Vd_-yZfPNsk

Even at lower efficiencies, the flexibility and low cost of OPV cells may have a market in low-cost lighting and phone charging systems for use among the 1.3 billion people living without access to an electricity grid, mostly in South Asia and sub-Saharan Africa.

The importance of storage

Because of the intermittent nature of solar energy, storage systems need to be deployed when direct consumption exceeds PV power generation, unless usage patterns can be changed to match supply or the excess can be fed into power grids. Future high-penetration PV roll-out will be facilitated by being coupled to storage technologies such as large-scale batteries, pumped hydro or direct chemical conversion. Storage capabilities in the network are generally desirable (in fact, storage is the most important missing ingredient of Australia's electricity network), and could assist not just with intermittent renewables such solar PV and wind, but would have widespread benefits across the network (see Chapter 3: Storage).

2.2 Solar thermal: A promising, large-scale technology

Large-scale solar thermal systems use sun-tracking mirrors to concentrate large amounts of sunlight on a central point to raise the temperature of that point high enough to drive a turbine, feed an industrial thermochemical reaction, or to create a heat reservoir that can be used at any time. Smaller, lower temperature systems can use lenses or troughs of mirrors to focus light along a line rather than to a point.

Global overview

CSP depends on direct solar radiation, and it performs best in arid and semi-arid areas with clear skies, the most promising being Australia, the Middle East, North Africa and South Africa, as well as areas in the US, Chile, Spain and India and the Gobi Desert region of northern China and southern Mongolia.

CSP is generally used to generate electricity, but it can also produce enough heat to drive endothermic industrial chemical processes (although commercialising a CSP-based Haber process remains a challenge) or to create a heat reservoir for use with heat pumps (e.g. space heating and cooling) or evaporative desalination.

Although CSP is a proven energy technology with a 30-year track record (the first commercial-scale facility was built in California 1984–90, and now has a 310 MW capacity), very large-scale facilities have been slow to emerge. This has accelerated in the past decade following a major initiative to encourage renewable energy, begun in 2004 by Spain—one of the European countries with the most hours of sunshine—and leading to rapid development of the industry. Global installed capacity has grown nearly 10-fold since 2004, with Spain, the US, the United Arab Emirates and India the major players.[22]

Global installed capacity of CSP systems was 4.3 GW at the end of 2014, according to the International Renewable Energy Agency.[23] An additional 2 GW capacity is under construction, and another 10 to 16 GW is planned. Spain remains the leader with installed capacity of 1042 MW in 2012, but rapid growth is likely to see the US, India, China, the Middle East and North Africa overtake Spain.[24] In 2011, the US Department of Energy announced its intention to bring solar electricity generation costs down to 6¢ per kWh by 2020—making solar cost-competitive with non-renewable electricity.[25]

One major proposal for CSP is the DESERTEC project, an ambitious US$400 billion initiative by a consortium of 20 large companies, banks, utilities and private foundations who want to harness solar power from sun-rich North Africa and the Middle East, and transfer the electricity via high-voltage transmission to consumption centres in Europe. The aim is to make CSP's contribution to Europe's electricity supply reach up to 16% by 2050.[26]

The IEA's CSP Technology Roadmap (2010)[27] forecasted that CSP could meet 1.3% of global electricity demand by 2020, 3.8% by 2030 and 9.5% by 2050. Cost parity with conventional fossil fuel generation was predicted to occur between 2020 and 2030.

22 Pool, S and Dos Passos Coggin, J 2013 'Fulfilling the promise of concentrating solar power', Centre for American Progress, June 2013.

23 Available at http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-csp.pdf

24 'Concentrating solar power: Technology brief', International Renewable Energy Agency, January 2013.

25 Pool, S and Dos Passos Coggin, J 2013 (op. cit.).

26 International Renewable Energy Agency, 2013 (op. cit.).

27 *CSP technology roadmap*, International Energy Agency (IEA), 2010.

In the context of global trends towards reducing the carbon intensity of electricity generation, technology continuing to reduce costs, and moves towards smarter, more distributed grids, it seems possible that CSP could play a significant role in meeting the remaining requirements for centralised, dispatchable supply.

Australian overview

CSP generation in Australia is still in its early uptake phase; only one genuinely large-scale solar thermal plant exists: a 9.3 MW linear Fresnel array used to pre-heat feedwater for the Liddell coal-fired power plant in NSW. Under construction is a 44 MW Fresnel array adjacent to the Kogan Creek coal-fired power station in south-west Queensland, due for completion in late 2016.[28]

As discussed earlier, Australia has the highest solar radiation of any continent, and there are no technical impediments to solar energy being a significant portion of our country's energy mix. The key challenges however are lower cost, dispatchability and flexibility. The latter is of particular importance. One of the attractions of CSP—its ability to be deployed in large capacities—has also been its Achilles heel in that markets in the past opted for the smaller, more modular renewable options such as wind and PV where the quantum of risk capital has been more manageable. This has resulted in CSP struggling to straddle the 'valley of death' that results from a need to demonstrate relatively expensive small- to medium-scale plants in order to provide confidence for the more cost-effective large-scale plants. Australia can play a leading role by developing versions of CSP that are viable at smaller capacities, and that have specific application in the mining and regional electricity markets, for example 20–50 MWe units with storage rather than the >100 MWe typical of plants using steam turbines. In addition, Australia should look to develop hybrid solutions where intelligent combinations of biomass or gas are used with storage to ensure CSP can provide firm supply.

Overview of current and future technology

There are four main variants of concentrating solar power (CSP) technology. In order of decreasing current installed capacity: parabolic troughs, solar towers, Fresnel reflectors and solar dishes. Parabolic troughs make up the vast majority of installed capacity (greater than 90%[29]) although solar towers and Fresnel reflector-based power plants are rapidly being scaled up commercially.

The future of CSP technologies will almost certainly see further development of their use for electricity generation and as heat sources for industrial thermochemical reactions. For electricity generation, increasing the continuous operating temperature would improve turbine efficiencies, and could be achieved by developing better reflectors (optimising size and geometry) and better receivers that absorb more light and transfer heat more rapidly. Cost and energy payback times could be further reduced by improving the design of reflector arrays in two ways: first, by optimising geometry to provide the same heat with less mirrors (e.g. using existing landforms), or second, by dematerialising the reflector infrastructure (e.g. using advanced materials or new manufacturing technologies).[30]

Better heat transfer systems could also reduce the energy requirements of the CSP plant itself, by reducing the heat required to keep molten salts molten overnight to prevent blocked, 'frozen' pipes.

Beyond the near-term research goals aimed at optimizing CSP technology on its own, CSP may be a candidate for hybridising with other solar or thermal technologies in new ways. For example, on a large scale, interesting variants of 'CSP-inspired' systems could be integrated into buildings or public spaces to increase the amount of light falling on PV arrays or provide space heating. On a medium scale, reflectors on tall commercial buildings could boost absorption chillers on their neighbours' rooves, or on a small scale, printed Fresnel reflectors could easily extend or fold from portable PV devices to increase performance.

28 Available at http://kogansolarboost.com.au/

29 International Renewable Energy Agency, 2013 (op. cit).

30 *Solar thermal electricity 2025*, AT Kearney GmbH, Düsseldorf, Germany, 2010.

Parabolic troughs

Long parabolic mirrors (up to 100 m long and 6 m aperture) focus sunlight on a central receiver tube in the focal line. Evacuated glass tubes with black interiors are used to minimise thermal losses and maximise light absorption, and a heat transfer fluid, such as oil or molten salt, is pumped (or thermo-syphoned) through the tube to collect the heat.

Advantages include the ability to scale up (to hundreds of MW) and the relatively low cost of single axis tracking. Disadvantages include long pipe runs and the heat requirements to keep the oil or molten salt viscosity low enough to flow through the pipes.

RIGHT: Parabolic troughs power the SEGS developments in California and provide 354 MWe from sunlight in the Mojave Desert. Image courtesy of Worklife Siemens.

Solar towers

Solar towers use vast arrays of heliostats (mirrors that track the sun in two axes) that all reflect light to the top of a (usually) central, raised tower. The maximum temperature at the receiver depends on the size and control of the heliostat field, but currently can reach around 600°C. This allows the use of dry steam, oil, molten salt, or direct steam generation to transfer the heat for use in electricity generation or to drive a thermochemical reaction (or storage, in the case of molten salt).

The central receiver atop the solar tower increases the concentration factor and reduces heat loss in the pipe-runs, so can reach higher temperatures than parabolic troughs. Solar towers do not cost-effectively scale down and are expected to contribute to centralised, large-scale grid distribution.

RIGHT: The PS10 solar power facility near Seville, Spain, was the first commercial project of its type and has been operating since early 2009. Image courtesy of Marco Cevat/flickr.

Fresnel reflectors

Fresnel reflectors are named after the French physicist who described how to approximate a large lens using smaller sections of it projected on to a flat surface. The approximation uses less material (and so reduces construction costs) but also makes the focal point less sharp. In the same way, a large reflective dish can be approximated with sections on the ground, and the resulting array is less efficient but significantly cheaper to build than either a big dish or a solar tower.

The array may look similar to a solar tower from a distance, but the maximum temperature is not as high and Fresnel reflectors currently only power direct steam generation from water.

ABOVE: A molten salt thermal storage project using a compact Fresnel collector in Albuquerque, New Mexico, USA. Image courtesy of Randy Montoya and Sandia National Laboratories.

Solar dishes

Solar dishes use a parabolic dish to track the sun and reflect sunlight to a single focal point (rather than a line, as parabolic troughs do). The resulting concentration factor can be very high, but the difficulty and cost of building them is also high. Supporting both a dish and its heated receiver on a two-axis tracker has limited the size of these systems and they have not been widely commercialised at scale for electricity generation. Pilot projects have so far generally produced less than 100 kW, but there may be a role for solar dishes as efficient, distributed power sources in a future smart grid, or to supplement other energy needs.

Pacific Northwest National Laboratory are testing solar dishes to supplement thermochemical conversion of natural gas to syngas. Image courtesy of Pacific Northwest National Laboratory.

Sources: adapted from material at http://reneweconomy.com.au and http://solar.org.au

2.3 Wind energy: Advances on land, offshore and in the air

Wind energy systems use rotors mounted above the ground to extract energy from passing air. The rotors drive turbine generators to produce electricity. The turbines are generally set atop tall towers and clustered in *wind farms* in regions with sufficiently strong and consistent winds. In Australia, such regions are commonly found on high ground and along exposed coast-lines, especially in the south-west, south and north-east of the continent.

Global overview

Wind energy is an established technology world-wide, and has been growing rapidly. Global wind energy installed capacity rose by 35 GW in 2013, increasing the total base by 12% to 318.1 GW.[31]

China has the largest share, with 91.4 GW of installed capacity. Of that 16.1 GW was new capacity, installed during the year. Collectively, the European Union—dealing with a shortage of open land by focusing on offshore wind—is the world's leading region, with a total of 117 GW of wind capacity installed.[32] Global wind power was producing 3% of global electricity at the end of 2014.

Australian overview

Australia is well placed to benefit from wind power, with many potential sites for large-scale wind farms across the country. However, large distances to high-density population centres, and the consequent very high transmission line costs, significantly reduce the number of viable options. As of 2014, there were 71 wind farms in operation, with 3.8 GW of capacity.[33]

Overview of current and future technology

The main development in wind power technology in recent decades has been an increase in the size of units. However, a number of research challenges remain; apart from improvements in turbine aerodynamics, structure and control, much research is aimed at operational issues. These include optimal control of wind farms, gearbox and generator condition monitoring, and blade erosion and repair. As with other variable sources, a key issue is energy storage. The capacity to time-shift energy availability from periods of high generation to low generation periods is crucial fo rgy supply.

Advances in turbine technology

Taller towers: Design advances, such as switching to concrete from steel, have made possible towers as tall as 100 metres or nearly 30 stories from base to nacelle (the part of the turbine that houses all the generating components). Benefits can vary by region, but as a rule of thumb, taller towers can boost output by up to 14% compared with a standard 80 m tower.

Better blades: As towers get taller, turbine blades get longer, creating a larger surface area to catch more wind. Stronger materials, such as carbon fibre or advanced fabrics used in new generation aircraft, are seeing turbine makers pushing the limits, allowing longer blades to begin spinning and generating power at lower speeds than earlier generations. Newer blades with a diameter of 120 m (versus previous 103 m standard) can deliver up to a 15% boost in output. Longer blades are also being tried to harvest powerful offshore gusts.

Upgraded controls: Improved sensors and precision controllers can constantly tweak the blade assembly's position to optimise the capture of wind energy, for example by adjusting the orientation of each turbine blade.

Advanced analytics software: Accurate wind forecasts can increase power dispatch by 10% by predicting wind strength, speed and direction up to a month in advance, or make short-term forecasting (zero to four hours in 15-minute intervals) specific to geography and topography down to individual turbines.

Sources: Adapted from: Technology gains are powering wind energy (Op-Ed). Available at: http://www.livescience.com/40525-tech-gains-powering-wind-energy.html Technology roadmap: Wind energy, IEA, October 2013 Wind power today, National Renewable Energy Laboratory, US Department of Energy, April 2009.

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31 Global wind report: Annual market update 2013, Global Wind Energy Council, 2014. Available at www.gwec.net/publications/global-wind-report-2/

32 *Global wind report: Annual market update* 2013 (op. cit.).

33 Available at http://www.cleanenergycouncil.org.au/technologies/wind-energy.html

Harnessing wind energy offshore

Offshore wind installations have much appeal; the Australian population largely lives on the coastal fringe, and wind resources could be harnessed in close proximity to our big centres without competing for onshore sites. Wind resources over open water also tend to be clearer and with less turbulence than over land.

Despite the obvious appeal, a number of challenges still remain for commercial development of offshore wind farms. Challenges include the additional complexity of construction, either in sinking deeper conventional undersea pylon foundations, or further exploring floating or submersible options for deep water. The ability of turbines to withstand the harsh conditions at sea will also be important, including constant corrosive attack by salt water. On an operational level, the cost of accessing offshore installations for maintenance dictate that design trade-offs have to favour robustness over efficiency.[34]

The US Department of Energy has been one of the strongest investors in offshore wind technology to date and has pursued research to develop and demonstrate the technologies, reduce the cost and increase uptake.

The IEA noted in 2013 that the size of the offshore wind resource is still attractive despite only a small fraction of it being technically exploitable. For example, around the US alone the offshore wind resource could provide about four times the total current US demand, which illustrates the potential of the technology as second only to solar energy at scale.[35]

Harnessing wind energy aloft

An intriguing concept is the airborne wind turbine. Rotors held aloft and tethered to the ground benefit from the higher speed and persistence of wind at higher altitudes, while avoiding the expense of tower construction. Power is transmitted to the ground via the conducting core of the tether. Published studies suggest airborne wind energy systems can produce electricity 10 times cheaper than conventional wind turbines, or less than 2¢ per kWh.[36]

In 2013, Google acquired Makani Power, a US company that is developing the concept. Tethered wings operate in groups of six, each anchored at the points of a hexagon, located between 250 and 600 m above ground. The company has successfully tested a 30 kW prototype that launched, hovered, generated power and landed without human intervention, and is testing a 275 m wing assembly with a 600 kW capacity in 2015. Makani believes large numbers can be built with fewer materials than towers, and says its robot wings can automatically land to avoid damage if wind speeds are too high or during bad weather.[37]

Another approach puts the turbines into the air, a concept known as “buoyant air turbines”. The Altaeros airborne turbine, developed by a Massachusetts Institute of Technology spin-off company, uses a helium-filled shell to support a lightweight turbine lifted up to 300 m into the air; such lifting technology has been adapted from tethered blimps that can stay up for months at a time.[38] An 11 m prototype was tested in 2012; an 18-month test run is due to begin in Fairbanks, Alaska in 2015. Being portable, computer-controlled and not needing a grid connection, such generators have commercial potential for deployment in remote areas, where electricity can cost many times more than the grid average.

2.4 Geothermal power: Energy from deep below

Geothermal energy comes from deep underground; the ambient temperature climbs the deeper you go. The temperature rise, known as the ‘geothermal gradient’, averages about 1 °C for each 40 m in depth, or 25 °C per kilometre. Most of this heat comes from the decay of radioactive elements, some of it was left over from the formation of the Earth, and the rest from the solar energy that heats the ground surface each day.

Global overview

Most high-temperature geothermal energy harvested for energy generation is done in regions close to tectonic plate boundaries, where volcanic activity rises close to the surface and is easy to tap. Conventional geothermal energy exploits natural circulation

34 http://energy.gov/eere/wind/offshore-wind-research-and-development

35 *Technology Roadmap: Wind Energy*, International Energy Agency, October 2013.

36 Goldstein, L. “Theoretical analysis of an airborne wind energy conversion system with a ground generator and fast motion transfer” *Energy, 55, pp 987–995 (2013).*

37 Rodriguez, S. “Google X to begin flying giant airborne wind turbines next month” *International Business Times*, 17 March 2015.

38 http://www.altaerosenergies.com/pressrelease_2014_03.html

of superheated fluids by tapping hydrothermal cells in the shallow subsurface and passing them through an energy conversion facility at the surface. Globally, regions with access to conventional geothermal resources (e.g. New Zealand, Iceland, El Salvador) can meet a substantial proportion of their electricity needs with geothermal power.

The global geothermal energy market has grown at a rate of 4% to 5% over the past several years. In 2014, 76 countries had active geothermal development projects, bringing the total global installed capacity to around 12 GW.[39]

Projected growth of geothermal power, based on planned or current projects, is for 17 GW installed by 2017, with a total of 12 GW additional power (double present capacity) being investigated.[40]

The global geothermal resource has been estimated at 42 million MW[41], which is orders of magnitude greater than the global total current energy demand, but as with all other diffuse energy sources (such as solar and wind) it is only technically feasible to capture a small fraction of the total resource.

Australian overview

Australia is exceptionally poor in conventional geothermal resources such as the well-known hydrogeothermal systems of neighbouring New Zealand. However, our potential unconventional geothermal energy resource is very large. A compilation of Australian geothermal resources, based on data reported by 10 publicly-listed geothermal companies as at December 2012, placed the size of the resource at 440,570 petajoules (or 122.4 million GWh) of recoverable heat—equivalent to about 16 billion tonnes of black coal. While substantial, its real size remains uncertain because of the lack of data about temperature at depth,[42] and Australia's actual installed capacity remains a tiny 80 kW (net) from a single unconventional resource in rural Queensland.[43]

While much of the focus on geothermal energy in Australia has been in relation to its potential for electrical power production, there are significant opportunities for geothermal heating or air conditioning in the built environment to reduce electricity demand.[44] Direct use applications are widespread in district heating in Europe, using the fact that the insulation properties of rocks mean that subsurface temperatures at only a few tens of meters depth are stable to seasonal surface temperature fluctuations. While there is growing awareness that such direct applications hold significant potential to lower the emissions intensity of the built environment, there has been relatively little experience in the Australian context, although examples exist in some cold climate locations, such as Canberra, ACT and Armidale, NSW.

Overview of current and future technology

There are many ways to extract and use geothermal energy, and only some of them—conventional geothermal energy technologies—are confined to areas where there are active volcanos, geysers or natural hydrothermal systems. Some form of geothermal resource is available just about anywhere on Earth, and a wide range of technologies has been developed to capture the various types of geothermal resources available. This section focuses solely on unconventional geothermal energy technologies because of the almost complete lack of conventional geothermal energy resources in Australia.

There are two main technologies suitable for large-scale electricity generation in Australia. Australian research has generally focused on engineered geothermal systems, in which wells are drilled into the deep, hot earth and water is pumped through a network of fractures in the hot rock, where it heats before being pumped back to the surface to drive some form of heat engine. Such resources can be difficult to prove without costly exploration drilling, and carry substantially more investment risk than other energy sources. The long development timeframe coupled to higher risk has so far presented a barrier to extensive commercialisation of this technology.

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39 Matek, B. 2014 *Annual U.S. & Global Geothermal Power Production Report,* Geothermal Energy Association, April 2014.

40 Keyes, N. "A deep well of experience: supporting Indonesia's geothermal development", World Bank, 12 May 2012.

41 World Energy Council 2013 World Energy Resources: 2013 Survey. World Energy Council. London.

42 *Looking forward: Barriers, risks and rewards of the Australian geothermal sector to 2020 and 2030*, International Geothermal Expert Group, Australian Renewable Energy Agency, July 2014.

43 Ergon Energy 2008. 'Birdsville Organic Rankine Cycle Geothermal Power Station'. Available at: https://www.ergon.com.au/__data/assets/pdf_file/0008/4967/EGE0507-birdsville-geothermal-brochure.pdf (webpage retrieved 4 April 2016).

44 Australian Academy of Science 2009, Australia's renewable energy future, Academy of Science, Canberra, January 2010.

The other main technology suitable for power generation is to use naturally occurring hot groundwater to drive some form of heat pump. Australia's longest running (and only) geothermal power plant at Birdsville, Queensland uses hot, artesian groundwater to drive an Organic Rankine Cycle-based power plant. The cooled water then supplies the town.[45]

Using geothermal energy to reduce electricity demand offers perhaps the most potential for Australia, especially in urban areas. The most common technology is the ground-source heat pump, which is very much like a normal air-source heat pump (e.g. reverse cycle air-conditioner) but uses the stable temperature a few metres below the surface as the source and sink of heat. This is much more efficient than using air, which typically fluctuates in temperature such that the pump has to maintain wider temperatures differences. The largest ground-source heat pump system in Australia is installed in the Geoscience Australia building in Canberra, ACT.[46]

A similar but more active system uses the stable underground temperatures as a 'heat bank' that uses groundwater to soak up heat during summer to provide summer cooling, and to return relatively warmer water in winter to provide heating. The energy consumed is the electricity to run the pump, which is much less than the amount of heating and cooling achieved.

Finally, geothermal resources can be used for direct heating and cooling applications. Examples include pumping warm groundwater into swimming pools (e.g. Claremont public pool, WA), piping it around homes or hotels in winter, or using hot groundwater for industrial cleaning or washing (e.g. Warrnambool, Vic).

Used in combination with other technologies, geothermal energy sources can be compatible with both centralised power generation and distributed approaches. It is the potential to reduce electricity demand in a way that is independent of the weather and the seasons that is possibly most helpful in the Australian context.

2.5 Ocean energy: utilising waves and tides

The oceans that cover 70% of the surface of the Earth offer two significant sources of renewable energy. *Wave energy* arises from the waves generated by winds blowing across the surface of the ocean; wave energy is therefore wind energy delivered in another modality. *Tidal energy* results from the regular rise and fall of the tides, and therefore has its origins in the interaction between the waters of the ocean and the gravitational pull of the Sun and the Moon.

Global overview

Energy from the oceans is distributed unevenly around the globe with the majority of wave energy occurring in the mid-latitudes where populated coastal regions provide strong demand for electricity. The total wave resource is estimated at 2 million MW, which is roughly double the current total electricity demand.[47]

IRENA described the global wave resource as being best "in medium-high latitudes and deep waters (greater than 40 m deep), where wave energy can reach power densities of 60-70 kW/m. Countries with the best wave energy potential are Australia, Chile, Ireland, New Zealand, South Africa, the United Kingdom and the United States with average power densities of 40–60 kW/m."[48]

Tidal energy is more spatially variable, but provides many locations with a predictable energy source that can provide good energy density from generation infrastructure.

The current level of development around the world is low considering the size of wave and tidal resources available and the proximity to demand in populated coastal regions. Most generation facilities are at the demonstration or pilot phases, but the industry has been forecast to grow up to $707 billion globally by 2050.[49]

45 Ergon Energy 2008 (op. cit.).

46 *Our building* Geoscience Australia. Available at http://www.ga.gov.au/about/facilities/building

47 Available at https://www.worldenergy.org/data/resources/resource/marine/

48 *Ocean energy technology brief*, International Renewable Energy Agency, June 2014.

49 Available at www.carbontrust.com/resources/reports/technology/marine-energy/

Australian overview

Australia's vast coastline—spanning both the wave-intensive mid-latitudes and a number of high energy tidal areas—may be capable of supplying more than 1,300 TWh of electricity per year, which is approximately five times our current total electricity demand.[50]

Wave power is currently deployed—either as trials or commercial demonstrations—in Western Australia, Queensland and Victoria; the largest of which is a 5 MW commercial demonstration plant that supplies the Garden Island Naval Base in Western Australia. Western Australia is also experimenting with wave-powered desalination that could reduce the electricity burden of its desalinated urban water supplies.[51]

Tidal energy pilot projects are currently underway in Queensland and the Northern Territory where the highest energy tides occur closest to population centres (as opposed to the sparsely populated north-west of the continent; Figure 5). A proposed demonstration project in the Clarence Straight, Northern Territory, would see an array of 456 single megawatt turbines. Strong potential for commercial development also exists in Victoria and Tasmania.

A number of Australian companies are pursuing the commercialisation of wave and tidal power generation and have demonstration or commercial developments operating in Canada, Northern Ireland, Scotland, France and New Zealand, as well as in Australia.

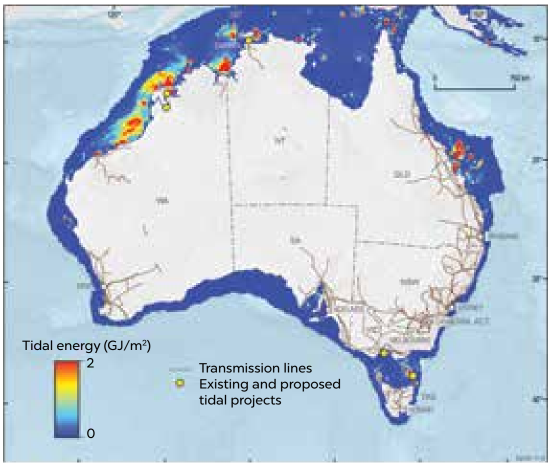

Figure 5: Total annual tide kinetic energy (in gigajoules per square metre, GJ/m^2) on the Australian continental shelf (less than 300 m water depth). Image courtesy Geoscience Australia.[52]

Overview of current and future technology

Wave and tidal energy require somewhat different infrastructure to capture.

Wave energy comprises both short-period waves whipped up by the wind (also known colloquially as 'chop') and long-period swell that forms by the energy of strong oceanic storms, travels hundreds of kilometres and gains a regular wavelength in the process. The local and choppy nature of wind waves is not amenable to electricity generation, as the waves are shallow, their wavelength is variable, the energy of each wave is low and they arise and calm quickly with variable weather conditions. By contrast, ocean swell persists long after the storms that create it and comprise powerful, regular waves that are relatively easier to extract energy from.

Three main classes of technology are used to extract energy from swell: oscillating water columns, oscillating bodies and overtopping converters. Oscillating water columns use wave surges to drive a stream of trapped air through an air turbine. Oscillating bodies use submerged or semi-submerged floats (buoys or platforms) that rise and fall with the swell. Many geometries and designs for transforming this movement to electricity continue to be trialed. Overtopping converters allow swell to deliver water over the top of a structure that captures it higher than the sea level to drive a low-head hydro-electric turbine. So far, no technology has established a clear market lead.

Australia, Canada and Israel lead the development of wave energy technologies, while Europe leads in uptake. Advances in materials and manufacturing-related sciences will continue to reduce costs, improve efficiencies and extend the service life of devices. The International Renewable Energy Agency reported in 2014 that costs are expected to fall 70% by 2030, mainly through economies of scale, which would make it competitive with diesel generation in isolated regions.[53]

Tidal energy can be harnessed in two main ways: rise-and fall systems and in-stream systems. For areas with large tidal ranges (e.g. Derby, Western Australia experiences 9 metre tidal rise and fall) the difference in height between low and high tide can be used to power low-head hydroelectric generators.

50 Hayward, J and Osman, P 2011 'The potential of wave energy', CSIRO.

51 IRENA 2014 (op. cit.).

52 Carson, L 2014. *Australian energy resource assessment*, 2nd ed, Geoscience Australia, Canberra.

53 Available at http://www.irena.org/DocumentDownloads/Publications/Wave-Energy_V4_web.pdf

This type of system is suited to tidal lagoons with a narrow mouth that can be barraged. For areas with narrow straights (e.g. between islands) or channels, fast tidal currents can be used to drive an in-stream generator. A variety of in-stream generators have been trialed including horizontal or vertical axis turbines, and oscillating hydrofoils that operate similarly to an aeroplane wing.

2.6 Bioenergy: A reliable, localised solution

Bioenergy is a term covering a diverse range of technologies, involving different feedstocks, processes and outcomes. Essentially, all of them extract energy from some form of plant material; solar energy that has been harvested by plants through photosynthesis.

The carbon dioxide emitted when biofuels are burned is produced at more or less the same timescale as the carbon dioxide that was taken in by plants while growing, so bioenergy or biomass fuels can be considered effectively net zero-emitters.[54]

Global overview

Global installed bioenergy-based electricity generation capacity was 82 GW in 2013, or about 3% of global electricity generation capacity, and conservatively forecast to grow gradually to 119 GW by 2017.[55] However, accelerated growth will depend on advances in densification processes and the commoditisation of biomass resources for power production, as well as the exploitation of cogeneration opportunities. If these are addressed, installed capacity could reach 128.5 GW in 2020.[56]

Australian overview

Australia's current bioenergy generation capacity stands at 2,400 GWh per year and has substantial scope for more considering the size of our agricultural sector. The main sources in Australia are burning sugar cane residue, followed by harvesting methane from landfill. Other sources include reusing pulp mill waste (black liquor) to help power pulp mills, harvesting sewage gas (methane), digesting agricultural and food waste, and burning wood waste. In total, bioenergy contributes approximately 1% of Australia's total electricity demand.[57]

An Australian example of advances being pursued is Renergi, a Curtin University spin-off company in Perth.[58] This firm is developing an advanced reactor that gasifies biomass to produce fuel for electricity generation. Its fuel comes from mallee shrubs, common in semi-arid areas of southern Australia. Fast-growing and producing strong new growth from the root crown after harvesting, it is ideal as a biomass resource. The gasification reactor is designed for remote areas far from the grid but close to resources such as mallee and wheat straw.

Two new bioenergy plants came online in 2013: Mackay Sugar's 38 MW plant began generating power for the Racecourse Sugar Mill, as well as delivering enough power to the grid to supply around one-third of Mackay's total electricity needs; and the 0.6 MW Colignan Cogeneration plant in Mildura, which uses food and agricultural waste for heat and electricity.

Australia's Clean Energy Council says that many "large sustainable biomass resources across the nation remain underutilised, and that bioenergy uptake is hampered by a difficult financial environment, policy uncertainty and grid connectivity issues". With the right policies, bioenergy has the potential to increase six-fold by 2020 to more than 10,600 GWh per year, and more than 72,000 GWh per year by 2050.[59]

Overview of current and future technologies

The nature of the feedstock and the intended use of bioenergy determines the most appropriate technology to employ in energy recovery. Many forms of biomass are available in large enough quantities to provide centralised electricity generation capacity (currently 1 to 100 MW in Australia; co-generation facilities are able to generate more), other forms of biomass are suitable to transform into fuels that can conveniently substitute fossil fuels in existing infrastructure (including liquid transport fuels or gas-fired electricity), and yet other forms are burned to recover heat.

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54 This contrasts with fossil fuels, where the carbon dioxide was absorbed over long periods, many millennia ago and is now being released very rapidly.

55 Medium-term renewable energy market report 2012, OECD/International Energy Agency, Paris, 2012.

56 Lawrence, M 2013 Biomass power generation, Navigant Research.

57 Clean Energy Council 2015, *Clean Energy Australia report 2014*, Melbourne.

58 Available at http://arena.gov.au/media/next-steps-for-innovative-biofuel-technology/

59 Available at https://www.cleanenergycouncil.org.au/.../bioenergy/.../Bioenergy-Fact-S.

Feedstocks

The most common biofuel in the world is wood, either in timber, pellet or charcoal form. It is an easy-to-handle, relatively safe and versatile feedstock with a good energy density. Other solid biomass feedstocks include various crop residues, commonly sugar cane, wheat, rice, sorghum and woody waste.

Cane sugar is an important biofuel feedstock used to produce liquid ethanol fuel. Liquid fuels can also be gained by extracting and denaturing plant oils. For example, peanuts and canola seeds each yield oils that are suitable for direct use as a fuel or for conversion to a fuel that is suitable for use in conventional engines or electric generators.

Crops grown specifically for biofuel production are also grown in some parts of the world, mainly Asia and Africa[60], although ongoing research is required to find suitable energy crops that do not compete with food production or conservation (e.g. palm oil) as the global population grows.

Novel feedstocks include sewage, animal waste, or food waste, all of which can yield gaseous fuels when digested correctly. Landfill sites also unintentionally act as anaerobic digesters that produce large amounts of methane, which can be captured and used as fuel.

Uses and technologies

Many bioenergy sources are mature technologies, especially those involving direct combustion of biomass. Wood, vegetation, dry animal manure and other biofuels have been burned for heat since ancient times and a number of technologies use the same principle, such as stoker boilers and garbage incineration with energy recovery. Other mature technologies include those that substitute a biologically derived fuel for a conventional fossil fuel, such as burning the methane from landfill or from anaerobic digesters in place of the methane from fossil fuel sources, or substituting petroleum-based fuels with plant oil-derived fuels.

All biofuels are combusted or used to generate products for combustion. While some biofuels are suitable for direct combustion, many sources of biomass cannot be burned directly (e.g. sewage or wet agricultural waste) or yield more efficient fuels if processed first (e.g. sugar is processed into ethanol). Established biofuel processing technologies include gasification, pyrolysis, fermentation and anaerobic digestion.

Biofuels are often mixed with other fuels in a co-combustion or co-firing arrangement based on availability or economics. For example, wood waste or biochar can be mixed with coal, or methane from landfill or animal waste can be combined with conventional natural gas. More effectively integrating biofuels with conventional fuels remains a significant opportunity.

Biofuel technologies are still being actively developed because of the strong potential for effectively carbon-neutral, energy dense fuels that can substitute fossil fuels in existing infrastructure. Newer technologies include bio-refineries and bio-hydrogen, as well as novel applications of microbial and algal culture.[61] Advanced processes involving pyrolysis and gasification that use novel or variable quality feedstocks is also an active area of research.

Being a relatively mature technology, the International Renewable Energy Agency forecast only modest cost reductions for bioenergy in the future, largely driven by the scale of uptake and specific technological advances, such as more efficient cleaning of gasses from anaerobic digestion processes to allow their use in high-performance turbines.[62]

2.7 Nuclear power: Opportunities for Australia

Nuclear reactors generate electricity much the same way gas or coal-burning plants do: by using a fuel source to heat water into pressurised steam, which then drives a turbine that converts the energy into electricity. The difference is how the water is heated—in nuclear plants the heat is released from the splitting of heavy atoms.

Nuclear power generation can achieve very low greenhouse gas emissions during operation. Mining and processing the fuel can, however generate sizable emissions if the whole energy lifecycle is taken into account. The energy density of uranium is far higher than any other conventional fuel, which is the key advantage of nuclear power. For example, one kilogram of uranium can yield the equivalent heat of 8 tonnes of coal. Hence, fuel—usually uranium—is a low proportion of power-generating cost.

60 International Renewable Energy Agency 2014 Global Bioenergy Supply and Demand Projections, IRENA, September 2014

61 International Renewable Energy Agency 2012, (op. cit.).

62 Biomass for power generation, International Renewable Energy Agency, June 2012.

Most of the cost of nuclear power—and indeed the greatest challenge facing the industry—is managing its waste, which cannot be discharged to the environment, as is current practice for combustion-based energy sources (e.g. coal-fired or biogas-fired power plants). Radioactivity remains high in nuclear waste materials for many decades, or in some cases centuries, before it can be handled safely or discharged to the environment, and it must be secured and contained for a long time.

Global overview

Nuclear power is an established technology. There are 435 commercial nuclear power reactors in the world, operating in 31 countries, and another 72 are under construction (the highest number in 25 years). The majority of those being built are in China, but also in India, South Korea and Russia. Existing reactors represent about 375 GW of global capacity and 11% of the world's electricity production.[63] Despite nuclear power being an established technology, improvements are continuously being made, allowing new and existing plants to produce more electricity; from 1990 to 2010 world nuclear power generation capacity rose by 17.5%, while output from reactors rose 40%.[64]

Australian overview

Australia is the only G20 nation without nuclear power, but has significant, relevant infrastructure. As noted by the World Energy Council:

"Australia has significant uranium resources and an adequate infrastructure to support any future nuclear power development. As well as the Australian Nuclear Science & Technology Organisation (ANSTO), which owns and runs the modern 20 MWt Opal research reactor, there is a world-ranking safeguards set-up–the Australian Safeguards & Non-proliferation Office (ASNO), the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) and a well-developed uranium mining industry. However, in contrast to most G20 countries, the only driver for nuclear power in Australia is reduction of CO_2 emissions, or costs arising from that. Apart from this, economic factors and energy security considerations do not make it necessary."[65]

The major impediments to nuclear power in Australia are economic, social and political, although the ground has been shifting on both fronts, largely due to the looming challenge presented by climate change and the need to drastically reduce greenhouse gas emissions.[66] Cost has also been an issue in the past, with Australia's low-cost coal power competing against the relatively high costs of nuclear power using the older technologies.

Opinion polls have shown a steady rise in public support for nuclear energy, reaching a high in June 2006 before falling sharply following the Fukushima disaster in Japan in 2011.[67]

On the issue of safety, figures compiled by the World Health Organisation, counting historical deaths from all sources—including mining, production, maintenance and pollution effects (although not accidents and long term health impacts) —show that nuclear is three times safer than wind, and 4,000 times safer than coal.[68]

Debate about nuclear power as part of the mix of low-carbon energy options for Australia's future has continued. The Australian Academy of Technology and Engineering (ATSE) drafted an action plan in 2014 calling for "the introduction of nuclear power to Australia by 2030"[69], which would, it said, "lead to very large savings to the economy through greenhouse gas emission abatement, more competitive electricity costs, improved health outcomes and reduced health costs over the decades following."[70] The Energy Supply Association of Australia (ESAA) also called for "the widest possible range of generation technologies" to be considered, including nuclear power, which might represent 20% of capacity by 2030–40.[71]

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63 Available at http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics

64 *Nuclear power in the world today*, World Nuclear Association, February 2015.

65 World Energy Council 2013 World Energy Resources: 2013 Survey. Available at https://www.worldenergy.org/data/resources/country/australia/nuclear/

66 'More Australians approve than disapprove of nuclear power plants although most concerned about disposal of waste', Roy Morgan Survey No. 4032, 10 June 2006.

67 Birda, DK et al. 2014 'Nuclear power in Australia: A comparative analysis of public opinion regarding climate change and the Fukushima disaster', Energy Policy 65: 644–653.

68 Nuclear: 0.04/TWh; coal-fired electricity (world average): 60/TWh; wind: 0.15/TWh.

69 Available at http://www.atse.org.au/atse/content/publications/policy/nuclear-energy-is-an-option.aspx

70 *Energy white paper*, Australian Academy of Technological Sciences and Engineering, February 2014.

71 Available at http://www.esaa.com.au/

In the next 15 years, the oldest quarter of the country's thermal generating capacity will likely need to be replaced, simply due to old age. This is at least 8,000 MW, practically all of it coal-fired. Replacing coal with gas would reduce emissions by 25–30 million tonnes of carbon dioxide per year, whereas replacing coal with nuclear would reduce emissions by 50 million tonnes.[72] In practice however, these figures may overstate the savings as they will be reduced by the contribution of renewable energy resources.

Overview of current and future technology

Six basic designs of nuclear reactor are currently operating today. Three designs dominate: pressurized water reactors (64%), boiling water reactors (15%) and pressurized heavy water reactors (12%). The remaining designs are gas-cooled reactors (UK only), light water graphite reactors, and fast breeder reactors.[73]

Some of these reactor types are being phased out—such as the light water graphite reactor design that failed at Chernobyl, Ukraine in 1986—in favour of safer and more efficient designs.

A number of new designs—known as Generation IV reactors—are under development for deployment by 2030. They are driven by the Generation IV International Forum, a consortium of 13 nations established in 2001. The consortium's technical goals are to develop reactors that:

- minimise waste volumes and the length of time waste remains radioactive
- produce 100–300 times more energy yield from the same amount of fuel
- have standardised designs to expedite licensing, reduce capital cost and construction time
- improve safety with simpler, more rugged designs, easier to operate and less vulnerable to accidents
- boost the cost advantage of reactors over other energy sources, and extend their operational life
- make the financial risk of nuclear power comparable to that of other energy projects
- are difficult to divert operations to weapons manufacture.

More than 100 nuclear power technologies were evaluated, and six reactor approaches were settled on for development, all operating at higher temperatures than today's reactors. Three are 'thermal' reactors—like today's reactors—and three are 'fast neutron' systems. In fast neutron reactors, existing nuclear waste is consumed in the production of electricity—a feature known as a 'Closed Nuclear Fuel Cycle'. Europe is pushing ahead with three of the fast reactor designs, and France—which produces 77% of its electricity from nuclear plants—has plans for half of its nuclear capacity to be replaced by fast neutron reactors by 2050.[74]

Another emerging technology that the International Atomic Energy Agency (IAEA) has projected may be deployed by 2025 to 2030 is Small Modular Reactors. IAEA describe them as "advanced reactors that produce electric power up to 300 MW(e), designed to be built in factories and shipped to utilities for installation as demand arises".[75] SMRs aim to be lower cost, faster to deploy and much more flexible than conventional nuclear power plants—properties that would potentially allow nuclear power to play a greater role in the more distributed grids of the future.

Thorium power reactors

Nuclear fission can be made to occur in thorium in addition to uranium, and such a reaction produces much less radioactive waste. Australia has the world's largest thorium reserves, making the development of a thorium fuel cycle here attractive. However, Australia does not have the resources to 'go it alone' on the necessary research. Collaboration with other countries would be necessary. A report by the UK National Nuclear Laboratory notes significant investments by several countries to overcome the technical barriers.[76]

72 *Australia's uranium*, World Nuclear Association, March 2015.

73 Canadian Nuclear Association, available at https://cna.ca/technology/energy/types-of-reactors/

74 *Generation IV nuclear reactors*, World Nuclear Association, August 2014.

75 International Atomic Energy Agency 2014 'Advances in small modular reactor technology developments: A Supplement to IAEA Advanced Reactors Information System' Vienna, Austria.

76 Available at http://www.nnl.co.uk/science-technology/position-papers/

India is a particular example, where there has been a national focus on the thorium cycle for power generation for decades; India lacks uranium reserves but is rich in thorium.

Nuclear fusion

Instead of splitting atoms as in fission reactors, fusing them (say, atoms of deuterium and tritium into helium) would release substantially more energy. If it is feasible, fusion would be the ultimate 'clean energy': no greenhouse gases, virtually limitless fuel (deuterium is distilled from seawater, and tritium 'bred' in the reactor), no chain reaction, and little waste. Hence, fusion has been attractive as a potential energy source for 60 years, but the technical challenges remain great. Work at the Joint European Torus project in the UK has proved fusion can be made to occur but major engineering breakthroughs are needed to take such a scientific advance to full-scale electricity-producing fusion power plants.

3 Storage: The missing link

Energy storage is one of the key technologies required for future energy grids. In Australia, like much of the developed world, electricity supply was developed by local governments in the 1880s. A recent review of the factors affecting technological change in the electricity industry noted that “as demand grew, isolated local networks were interconnected and electricity was supplied from central power stations. In most countries, grids were designed to generate electricity from fossil fuels, such as coal or oil, providing power via a centralised grid, and this model has stayed largely unchanged for more than a century.” [77]

To ensure a reliable supply at all times, generators and networks must be planned and constructed to meet the highest expected loads, so the system is sized for the peak loads. The nature of the electrical network requires that supply of electricity must always match the demand. So as the load changes, then generation must follow. This adjustment occurs on a minute-by-minute basis (even second-to-second)—requiring some generators to be kept operating at partial capacity waiting for signals from the network operator to adjust their output up or down as required. Failure to achieve this delicate balance can lead to system failure (blackouts). The entire network has to be designed, built and run to meet peak demands, even though such demand may only occur for a few tens of hours a year. The advantage of flattening peak demand is illustrated in Figure 6.

The traditional system has worked well over the last half century. However the centralised, remote power generation model was not designed to cope with increasing amounts of local and variable generation arising from new technologies, such as solar PV and wind power. These power sources are distributed across the network, or close to consumers (such as rooftop PV) and are mostly uncontrolled—with their output dependent on a variable resource. With increasing penetration of these power sources, maintaining the delicate balance between supply and demand becomes

77 ACOLA 2015 ‘Technology and Australia’s future: New technologies and their role in Australia’s security, cultural, democratic, social and economic systems, Australian Council of Learned Academies, September 2015. (Appendix 2)

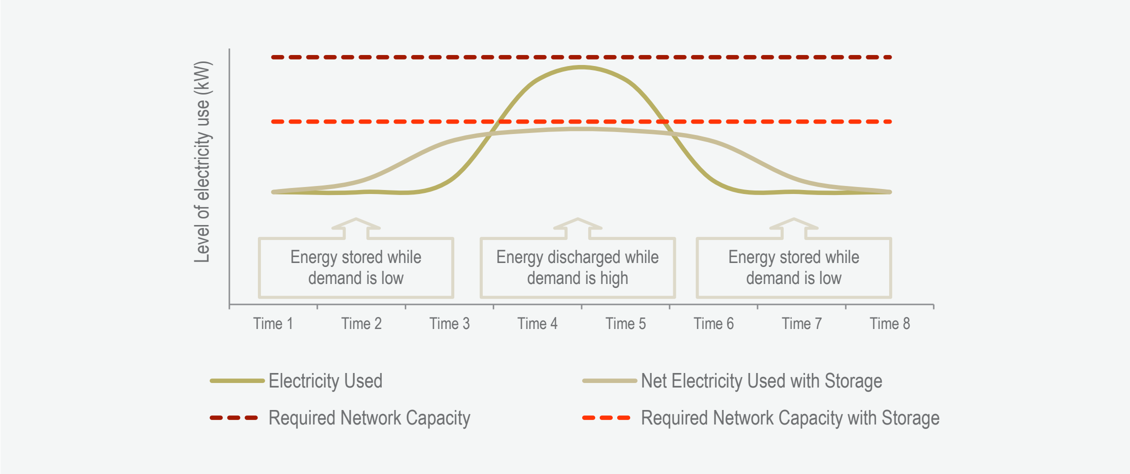

Figure 6: Peak flattening using energy storage. Image courtesy Marchment Hill Consulting 2012. Used by permission.

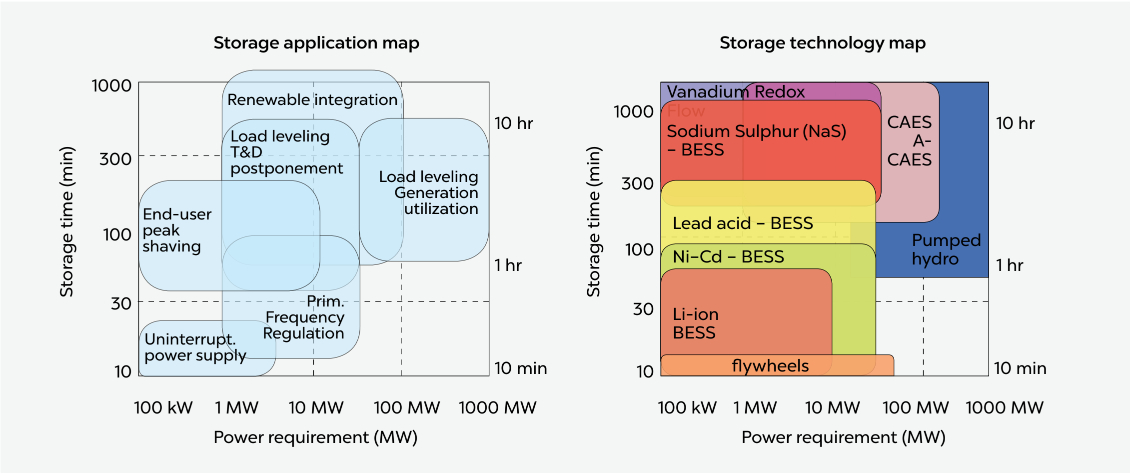

Figure 7: Storage applications and technologies maps. Image courtesy MIT Energy Initiative from a presentation by Ernst Scholtz, ABB. Corporate Research at the MIT Energy Initiative Associate Member symposium, April 2011.

increasingly difficult. Energy storage can help deal with the inherent variability of the existing grid, as well as provide more flexibility.[78] It can provide the necessary buffer between variable load and variable generation.

The operational timescale needed for stored energy is diverse, ranging from milliseconds and hours, to days and months (i.e. seasonal). Energy storage to maintain power quality requires very rapid charge/discharge cycles, but the total amounts of power required (for example, to maintain frequency) may be relatively small. For applications that need to absorb power for a few seconds, supercapacitors, flywheels and superconducting magnetic energy storage may be appropriate. For periods of minutes to hours, batteries are the best, with many different types in use and under development. The different storage options are set out in Figure 7.

Centralised large-scale storage

Energy storage in the form of hydroelectric dams is already widely deployed in many electricity grids. In these hydroelectric systems, surplus energy is used during times of low demand to pump water to an elevated reservoir; at times of high demand, the water can be rapidly released through turbines to recover electricity. Australia has some 1,500 MW of pumped hydro energy storage, mostly in New South Wales (the Snowy Mountains and Shoalhaven schemes) and southern Queensland (Wivenhoe Dam).[79]

Pumped storage is by far the most widely used form of grid-connected energy storage globally, and the technology is mature.[80] However, it is dependent on suitable sites, environmental

78 *Bottling Electricity: Storage as a Strategic Tool for Managing Variability and Capacity Concerns in the Modern Grid*, Electricity Advisory Committee, U.S. Department of Energy, December 2008.

79 Hearps, P et al. 2014 Opportunities for pumped hydro energy storage in Australia, Melbourne Energy Institute, February 2014.

80 Decourt, B et al. Electricity storage, SBC Energy Institute, 2013.

impact, and is mostly deployed as a centralised, large-scale option. Globally, there is about 100 GW of pumped hydro storage capacity, and another 10 GW of other technologies.[81] Recently, some investigations have been made into smaller-scale versions of pumped storage, using dams.[82]

Another large-scale storage technology used on centralised systems is compressed air energy storage (CAES). This is dealt with in Section 3.2.

Decentralised storage

More recently, *decentralised or distributed energy storage* has emerged and is expanding rapidly. It is used in residential, commercial and industrial applications, such as off-peak hot water supply (thermal energy storage) and, more recently, in batteries. It allows storage to be located close to the energy end-user, providing more flexibility and interacting at the distribution and retail level of the market, where electricity pricing is much higher than at the transmission level. Batteries or other electrochemical energy storage systems are attractive as they can be scaled, are quiet, can be highly efficient, flexible and increasingly long-life.

Storage can also be located near the energy producer. The European Energy Research Alliance and the European Association for Storage of Energy labelled decentralised storage as 'the perfect match' when it can be coupled with renewable energy sources, as "it can smooth out the peaks and troughs of variable supplies from renewable energies … and making this available when consumption is high or generation output low. Even relatively small storage facilities near to the point of production may have far-reaching implications for the design and operation of the electricity distribution grids of the future, not least smart grids."[83]

Energy storage can improve the operation of most parts of the electricity system, and at a range of scales. Individual consumers can respond to price signals (usually aimed at reducing demand in peak times) by using their stored power during peak times when prices are high, and recharging their storage in off-peak times (i.e. load shifting), or to remain unaffected by black-outs. On a local grid level, storage can be used to 'island' parts of the grid to maintain power during outages. For large, central generation facilities, energy storage capacity can be used to buffer against sudden peaks or changes in network demand or to cover demand peaks that would otherwise require new infrastructure to service.

Besides preventing grid failure or reducing planned curtailment events, stored electricity can also more readily re-start power generation facilities than the diesel generators that have traditionally been deployed following major outages.

Demand for grid storage is growing rapidly: worth only US$200 million in 2012, it is forecast to reach US$10.4 billion by 2017, according to Lux Research. Navigant Research estimates global installed grid storage revenue will reach US$605.8 million in 2015 and grow to US$21.5 billion in 2024.[84]

In April 2015, the US Department of Energy's *Quadrennial Energy Review* identified energy storage as a critical piece of energy infrastructure, and called for a national energy system storage strategy to coordinate a multi-billion dollar investment in energy storage systems by government, utilities and industry.[85]

In addition to pumped hydro, there are **four broad types** of storage technologies in use or under development. Recent developments in these technologies will be discussed in the pages ahead. They are:

» **Electrochemical:** Power is stored as chemical energy, such as in the familiar lead-acid car battery.

81 *Electricity storage: Technology brief*, International Renewable Energy Agency, April 2012

82 Blakers, A 2014, 'Mass energy storage using off-river pumped hydro', Asia-Pacific Solar Research Conference, Sydney, November 2014.

83 EASE & EERA, 2013. *Joint recommendations for a European energy storage technology development roadmap towards 2030*,

84 *Grid storage: State of the market*, Lux Research Inc, March 2012; and *Energy storage enabling technologies: Global market analysis and forecasts*, Navigant Research, April 2015.

85 *Quadrennial energy review*, US Department of Energy, April 2015.

- **Conventional batteries:** Electricity is stored as chemical energy and rechargeable; originally developed for portable devices and now being up-scaled, with a range of chemistries in use and under development, e.g. lithium ion.
- **Redox flow batteries (RFBs):** Battery technology where the energy is stored directly in the electrolyte solution. An advantage of this technology is that the storage capacity can be increased through larger electrolyte tanks. It is also expected that flow batteries can provide lower cost storage at large scale.
- **Hybrid RFBs:** Utilising more than one type of charge storage mechanism.
- **High temperature batteries:** Use molten metals and molten salts as an electrolyte and offer high energy density and a high power density.
- **Hybrid batteries:** Combine conventional and advanced technologies, for example batteries with supercapacitors.

» **Mechanical:**

- **Compressed air:** Stored in low-cost buffers (such as caverns) and used to power turbines on demand.
- **Cryogenic storage:** Also known as liquid air energy storage (LAES), where power is used to liquefy air, which can then be stored for short- or long-term use.
- **Flywheels:** Mechanical devices that harness rotational energy, which can be converted back to electricity.

» **Supercapacitors and superconducting magnetic storage:** Supercapacitors store electrostatic energy, usually between parallel plates; superconducting magnetic storage promises very high efficiency storage.

» **Power to gas:** The production, storage and use of hydrogen or methane are also considered by some to be a form of energy storage. Here, electricity is converted into hydrogen by electrolysis, and the hydrogen stored and used later to generate power via fuel cells.

Energy storage technologies are vastly different in design and application. There is no single 'best' storage solution that applies to all situations, but a range of options depending on needs and conditions. Often, local conditions—such as demand, load, topography or distance from a grid—determine those technologies which are most efficient and economical to deploy. Nevertheless, they deliver benefits regardless whether the energy source is coal, gas, renewables, or a mix of these. In determining which storage system is best suited for a particular location or application, the key parameters are:[86]

» **Power rating (kW or MW):** The amount of power that can be supplied.

» **Discharge time (seconds, minutes, hours, days):** The period of time over which the technology can release its stored energy.

» **Specific energy (watt-hours/kg):** The amount of energy that can be stored per unit weight.

» **Energy density (watt-hours/L):** The amount of energy that can be stored per unit volume.

» **Cycle life:** The number of charge/discharge cycles it can deliver in its lifecycle.

Table 1 provides a summary of different energy storage technologies outlining key features, their primary applications and challenges

3.1 Electrochemical storage: conventional, redox-flow and other batteries

Conventional batteries

Lead-acid batteries are quickly losing ground as the most common battery for both vehicles and off-grid power supply systems. Lithium-ion batteries are ubiquitous in portable devices, and various lithium chemistries are the most likely options for widespread adoption in electric cars and to store domestic or distributed renewable energy. In lithium-based designs, there are many variants for the positive electrode, each with pros and cons. Materials include lithium-nickel-cobalt-aluminium oxides (NCA), lithium-nickel- manganese-cobalt oxides (NMC), lithium- manganese-spinel (LMO), lithium titanate (LTO) and lithium-iron-phosphate (LFP).

The negative electrode is usually graphite, though silicon has been used, and lithium titanate is now found in some commercial devices. Lithium titanate has exceptional lifetime, but is currently much more expensive than graphite. New electrode materials are being actively developed. There is some concern

86 Parameter descriptions reproduced from ACOLA 2014 (op. cit.).

about lithium-ion battery safety, since for some chemistries and cell designs abuse can result in venting and fire. For this reason, charging regimen and overall cell/battery management must be well controlled. Newer prismatic designs and chemistries (LTO and LFP) have been shown to be very tolerant to abuse.

An example for large-scale storage using lithium-ion is the Laurel Mountain facility in West Virginia in the US, where a 98 MW wind power plant has been operating an 8 MWh storage solution using advanced lithium-ion batteries for frequency regulation and renewable energy integration since October 2011.[87]

Conventional batteries for home energy storage are currently in the early uptake phase, and Tesla Motors announced in May 2015 that it intended to accelerate the uptake dramatically.[88]

Redox flow batteries

Redox flow batteries (RFBs) differ from conventional batteries in that the active material is contained in a liquid electrolyte that flows over the surface of non-reactive electrodes. The main advantage of RFBs is that they can easily be scaled up by increasing the size of the electrolyte tanks to increase the capacity of the battery.

A range of different RFB chemistries have been commercialised, and several others are under active development. The best-known RFB is the vanadium redox battery (VRB), developed at the University of New South Wales in the 1980s and which uses vanadium in both tanks. The iron-chromium flow battery has a number of desirable characteristics but might not achieve widespread commercial production. The zinc-bromide battery shows substantial promise as the technology has been proven in a number of trials.

A US Department of Energy research program to “bring VRBs to market by 2015” delivered improvements that increased energy storage capacity by more than 70%. This led to commercial deployment: US utility SunEdison purchased 1,000 VRBs to store electricity generated by the company’s rural electrification and solar powered microgrids in India, which will store more than 100 MWh of power.[89]

Hybrid RFBs

Hybrid redox flow batteries can be considered as a hybrid between conventional batteries (in which a solid electrode participates in the reaction and shares the same space with the electrolyte) and true flow batteries (in which the electro-active species are all dissolved). As such, hybrid RFBs use a solid electrode in conjunction with electrolyte storage tanks, and the energy of the cell is determined by the chemistry, the size of the tanks and the surface area of the electrode.

Zinc-bromide batteries are the most widely known example of hydrib RFBs and are entering commercial mass production in the grid-connected, distributed energy storage market.[90]

Charging the battery deposits metallic zinc on the anode (analogous to a conventional battery anode) but also forms bromine, which is complexed by organic molecules to keep it in solution for storage (analogous to a flow cell). A number of zinc-bromine batteries are under development by companies in the USA and China, and by RedFlow Ltd in Australia.

Another hybrid RFB chemistry is zinc–cerium, which has been extensively studied in the laboratory and at the industrial pilot scale since its introduction in 2005 by UK company Plurion. Zinc-cerium cells promise to provide very cost-effective energy storage, but remain at the research stage, mostly in the UK.

High temperature batteries

Some battery chemistries require elevated temperatures for operation. The best known of these is the sodium-sulfur battery (NaS) commercialised by NGK of Japan. These batteries operate between 290 and 360°C, the temperature range at which sodium and sulfur are molten. The NaS battery is capable of both high power and high energy operation, being limited mainly by thermal dissipation. A NaS battery system is made up of many modules, each containing 320 individual cells. A 2 MW NaS battery consists of 40 x 50 kW modules, containing a total of 12,800 individual cells, providing 6 hours of output at 2 MW.

87 Available at http://energystorage.org/energy-storage/case-studies/frequency-regulation-services-and-firm-wind-product-aes-energy-storage

88 Available at http://www.teslamotors.com/en_AU/powerwall

89 ‘SunEdison to purchase 100+ MWh of flow batteries’, SunEdison press release, 27 March 2015.

90 See for example: https://zcell.com. ZCell offers 10 kWh systems for domestic and office applications.

Table 1: Key features of different energy storage technologies. Source: Refraction Media

	Power rating	Efficiency	Storage	Discharge time	Self-discharge/ day	Energy density	Cycle life	Lifetime	Energy cost	Maturity	Environmental impact
Pumped hydro	This system uses two reserves to separate water vertically. Water is pumped uphill during off peak time and released at peak times, the flow of water drives turbines. Pumped hydro is the main form of energy storage worldwide. Its primary application is for energy management and backup reserves. **Challenges:** large capital cost involved in building facilities, geographic limit, environmental impact.										
	100–5000 MW	65–85%	Hours to months	1–24hrs	0%	0.5–1.5 Wh/kg	2–5 x 10^4	40–100 years	US$5–100/ kWh	Mature	Requires geological structure.
Compressed air	Air is pumped into storage at high pressure and released at peak. During discharge air is combined with fuel (natural gas) and combusted then passes through turbines. As the air expands, energy is released. Its primary application is for energy management, backup reserves and it can be used to integrated renewables. **Challenges:** geographic limit, slow response time, low efficiency, environmental impact.										
	5–300 MW	42–54%	Hours to months	1–24hrs	0%	10–60 Wh/kg	5 x 10^3 – 2 x 10^4	20–45 years	US$2–50/ kWh	1st Generation deployed, 2nd Generation demonstration	Requires geological structure. Combustion emissions. Storage of high pressure gases.
Flywheel	Rotating mechanical device that is used to store energy. Its primary application is in load levelling and frequency regulation. **Challenges:**rotor tensile strength limits, limited energy storage time due to high friction loss. Although if operated in a vacuum the amount of friction is reduced improving efficiency and reducing damage to device.										
	0–250 kW	85–95%	Seconds to minutes	millisec –15mins	20–100%	5–130 Wh/kg	10^5–10^7	20+ years	US$1000–5000/kWh	Deployed	Minimal environmental impact.
Batteries	Convert stored chemical energy into electrical energy, the reversible reaction allows for recharge. Different battery types: lead acid, NaS, Li-ion. Li-ion batteries can be used for power quality and frequency regulation. **Challenges for Li-ion batteries as an example:** scalability, high production cost, sensitive to temperature.										
	0–40 MW	60–95%	Seconds to months	Seconds–hours	0.1–20%	25–250 Wh/kg	100–10^4	3–20 years	US$200–2500/kWh	Research stage to mature	(+ve) Li and metal air battery materials can be recycled. (-ve)Toxic materials, fire hazard
Fuel cells	A fuel cell converts chemical energy to electricity through a chemical reaction with oxygen or an oxidizing agent, it requires a constant source of fuel. Primary application for power quality and energy management. **Challenges:** cost.										
	0–50 MW	40–60%	Hours to months	Seconds–days	0%	800–10,000Wh/ kg	1000+	5–15 years	–		Use of fossil fuels.
Thermal	Allows excess thermal energy to be stored for later use. A range of technologies can collect thermal energy each with their own performance and application characteristics e.g. solar, heat or cold produced from heat pumps, geothermal, heat and power plants. Challenges: storage performance stability, cost.										
	0–60 MW		Minutes to months	1–24hrs	1%	80–200 Wh/kg	–	10–20 years	–		Reduce energy consumption, CO2 and emissions.
Superconducting magnetic	Stores electric energy in a magnetic field within a cooled super-conducting coil. High efficiency and fast discharge time. Primary application in power quality and regulation. **Challenges:** low energy density, cost.										
	0.1–10 MW	95%	Minutes to hours	millisec –5mins	10–15%	0.5–5 Wh/kg	10^4	20+ years	US$1000–10000/kWh	Research and development stage	Large magnetic fields on human physiology.
Supercapacitor	This is a hybrid between batteries and capacitors. Supercapacitors store energy in the electric field between a pair of charged plates. The primary application is for load levelling and stabilisation. They are capable of fast charge and discharge and have a long life cycle. **Challenges:** cost.										
	0–300 kW	95–98%	Seconds to hours	millisec–1hr	20–40%	0.1–15 Wh/ kg	10^4	20+ years	US$300–2000/kWh	Development to demonstration stage	(+ve) Enhance energy performance of cars. (-ve)Materials for construction and ultimate disposal.

The high capacity and output of NaS batteries means that they are suitable for large-scale applications such as time-shifting wind farm and PV output, load-shifting at sub-stations, voltage support and emergency power supplies. They are well suited to the integration of renewable energy sources with the grid, and are capable of ramping up their output from zero to 100% of maximum power in less than 10 seconds. However, a major fire that took two weeks to extinguish in 2011 required a substantial redesign of all further NaS batteries.[91]

Liquid-metal batteries also operate at high temperatures, and use two liquid metal electrodes separated by a molten salt electrolyte that segregates into three layers based on density and immiscibility.[92] The liquid metal is very conductive and so provides high voltaic efficiency and power, and there is no requirement for a separator as the metals are kept from coming into contact by the electrolyte. A wide range of suitable metals is available, as binary and ternary alloys can be used, and practical temperature ranges are from room temperature to 1,000 °C. It remains to be seen if they can be cost-effectively manufactured, but it is under active development.

Hybrid batteries

The CSIRO-developed *Ultrabattery* is an example of a hybrid lead-acid battery using more than one type of charge storage mechanism. CSIRO describe the system as "a hybrid energy-storage device, which combines a supercapacitor and a lead-acid battery ... integrated into one unit cell by internally connecting the negative plates of the battery and the supercapacitor in parallel".[93] The supercapacitor handles sudden changes in charge better than a lead acid battery, and the battery stores charge over longer timeframes than a capacitor can. The combination of the two allows (almost) the best of both worlds: higher efficiency and longer cell life. The battery has been commercialised by energy storage company Ecoult (a 2007 CSIRO spin-off that was acquired by a US company in 2010), and is being used to provide ancillary services in North America. The battery is also installed at wind and solar PV farms in Australia and elsewhere for output smoothing.[94]

Another design is the aqueous hybrid ion (AHI) battery developed by Carnegie Mellon University and spun-off as Aquion Energy with venture capital backing. The Aquion device uses ion intercalation in the electrode to create a capacitor-like self-balancing property, which allows cells to be stacked to high voltages without the need for control circuitry.

The system was designed with the explicit goals of safety, low lifecycle costs and long cycle life, so has potential widespread application in stationary applications.[95]

3.2 Mechanical storage: Compressed air, cryogenics and flywheels

Compressed air energy storage (CAES)

If no chemical reactions occur, the energy of a gas is a function of its volume, temperature and pressure, and the amount of energy that can be stored is a function of how much each of these variables can be changed. Energy storage by compressing air and recovery by forcing the compressed air through a turbine is an established technology but there are only two major plants in operation. The plant at Huntorf in Germany can store 290 MW for four hours; and that at McIntosh in Alabama 110 MW for 26 hours.[96] Both plants use underground caverns that were created from solution mining operations as the air reservoir: the cost of building large enough tanks would be prohibitive.

Changing the pressure of air also changes its temperature: compression to the 70 bar operating pressure of CAES systems generates large amounts of heat, which can be recovered. However, when the air in the reservoir expands again (i.e. during generation) it cools by the same amount, and requires heat to prevent a

91 NGK Insulators, Ltd. Cause of NAS Battery Fire Incident. June 2012. url: http ://www.ngk.co.jp/english/news/2012/0607.html

92 Kim, H et al. 2013 'Liquid metal batteries: past, present, and future'. *Chemical Reviews* 113: 2075–2099. 86 Wood, J. 2012 'Grid-scale energy storage. Demonstration for ancillary services using UltraBattery', Energy Storage Program, US Department of Energy.

93 CSIROpedia: UltraBatteryTM Available at: https://csiropedia.csiro.au/ultrabattery/

94 Wood, J. 2012 'Grid-scale energy storage. Demonstration for ancillary services using UltraBattery', Energy Storage Program, US Department of Energy.

95 Whitacre, JF et al. 2012 'Large format aqueous electrolyte polyionic devices for low cost, multi-hour stationary energy storage', Aquion Energy.

96 Available at http://www.apexcaes.com/caes

thermally-induced pressure drop from reducing efficiency. Waste heat from a combustion turbine can be used for this purpose.

The advantage of CAES in future grids may be its ability demand-shift: to store energy when it is available—such as during off peak times or when there is surplus wind power—and generate dispatchable power very quickly to service peaks. In this sense, CAES and pumped hydropower share similar characteristics, with the exception that CAES is not drought sensitive.

Smaller, above-ground CAES systems are also being developed, and need not be limited to air. The substantial volume of natural gas pipelines may provide an attractive additional energy storage mechanism, if the systems can be made to operate isothermally and safely.

Traditional heat exchange technology has not been effective, so research into new techniques is underway. One approach which has recently been demonstrated is the use of aqueous foam-based heat exchange. In this approach, a water-based foam is injected into the compression chamber providing near isothermal conditions for compression and expansion. A 1.5 MW demonstration is operating in the USA.[97]

Liquid air energy storage (LAES)

In this technology, power is used to liquefy air, which is then stored for short- or long-term use. When discharge is required, the liquid air is gasified and drives an expansion turbine to produce electricity. LAES has been demonstrated, and has some attractive aspects (such as long-term low-loss storage and industrial scale of air liquefaction being an established technology). However it too suffers from low round-trip energy efficiency, largely due to the thermodynamic cycles involved.[98]

Flywheel energy storage (FES)

Flywheels use motors to convert electrical energy to kinetic energy and keep a perfectly balanced rotor spinning almost indefinitely in a sealed, near-frictionless cylindrical casing. The same motor can then be driven in reverse to yield power on demand.

FES is particularly suitable for applications that require short duration, high energy power, such as to provide backup to cover network fluctuations or minor failures, or to provide alternative supplies to avoid switching major loads.

Depending on size, flywheels can be charged in seconds to minutes so can respond much more quickly to changes in power availability than conventional batteries. They can also discharge much more quickly and deeply without damage, and last many thousands of full discharge cycles. For this reason, they are used in medium to large-scale (kWh to MWh) uninterruptable power supplies, particularly in telecommunications.

Recent advances in FES include reducing friction by using magnetic levitation instead of conventional ball bearings and mounting the rotor in high-vacuum conditions. The size of FES systems has also been reduced by increasing rotational speed while reducing the mass of the rotor, but they remain suitable only for stationary power storage applications.

3.3 Superconducting magnetic storage and supercapacitors

Superconducting magnetic energy storage (SMES)

Magnetic fields can be used to store energy, and superconducting magnets offer a very low-loss way to implement this type of storage; at very low temperatures some materials lose all resistance to electric current. As an example, the superconducting magnets at the CERN Large Hadron Collider store some 3 MWh of energy. Superconducting magnets are now widespread in medical and scientific applications, but typically require the use of liquid helium (cooled to 4.2 kelvin, or −267 °C) and liquid nitrogen (cooled to 77 kelvin, or −196 °C).

Superconductors were first described in 1970, with the first demonstrations and application to the electricity grid in the 1970s and 1980s.[99] A great advantage of SMES is the high conversion efficiency, since losses in the superconducting coil are extremely low. These devices have a very fast response and are also able to charge and discharge at very high power (i.e. high power density), and can switch between charge and discharge extremely quickly. There are no moving parts in the storage device, leading to potentially very long lifetimes.

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97 Available at http://phys.org/news/2013-09-sustainx-mw-isotherm-compressed-air.html

98 Morgan, R et al. 2015 ‘Liquid air energy storage: Analysis and first results from a pilot scale demonstration plant’, *Applied Energy* 137: 845–853.

99 Tinador. P 2008 ‘Superconducting magnetic energy storage: status and perspective’, IEEE/CSC & ESAS European Superconductivity News Forum No. 3.

While *power* dense, the *energy* density of such storage is quite low. These characteristics led to storage applications that serve power quality, such as voltage and frequency control, rather than energy management over minutes or hours.

To date, there have been few implementations or demonstrations of SMES, as considerable technical and economic challenges must be overcome. The large mechanical forces generated by the intense magnetic field necessitate robust (and bulky) magnet designs. Substantial cooling power is required to maintain the low temperatures. Conventional superconducting wire (such as niobium-titanium alloys) is limited to liquid helium temperatures, with the associated cooling costs; while the more recently developed 'high temperature' superconductors remain very expensive and hard to assemble into efficient solenoid designs.

Supercapacitor energy storage

Capacitors are widely-used passive electrical components that store energy through the process of 'charge separation'. They contain at least two electrically-conducting plates with opposite charge signs, separated by a non-conducting *dielectric*. The dielectric increases the capacitor's charge capacity, and energy is stored in the electrostatic field between the plates.

Supercapacitors (also called *ultracapacitors*) utilise high surface area materials and/or electroactive materials to provide much greater capacitance than conventional capacitors. This allows their use in energy storage applications. Supercapacitors made using high surface area materials (such as activated carbon) utilise an electrolyte, and store charge in the electric double layer which forms on the surface of the electrodes. Supercapacitors using electroactive materials rely on the transfer of an electron, with charge storage through a process called pseudo-capacitance.[100]

Supercapacitors can be broadly classified into two categories: those using *aqueous* and those using *organic* electrolytes. Aqueous systems have low resistance and are capable of high power, while organic electrolytes are not as conductive but can hold higher voltages. Energy storage increases with voltage squared, so higher voltage devices can be quite useful. In practical terms, this translates to high power but lower energy for aqueous systems, and higher energy but lower power for non-aqueous systems. As with batteries, individual cell voltages range from around 1–4 V, so higher voltage devices require a number of cells in series.

Supercapacitors have a number of attractive characteristics for energy storage, as well as some limitations. Typically, supercapacitors are capable of very high cycle life—potentially millions—since there should be no chemical processes occurring, as in batteries. In practice, their cycle life may be limited by packaging and/or material degradation.

Supercapacitors can support very rapid charge and discharge cycles, but currently store much less energy per unit mass or volume than batteries. Recent developments have shown that greatly increased specific energy is possible; some supercapacitors may approach the specific energy of some batteries.[101]

The Australian company CAP-XX Pty Ltd developed a high power/medium energy product in conjunction with the CSIRO in the 1990s, which was the basis for their current product line.

3.4 Power-to-gas

Conversion of electrical power to hydrogen via electrolysis is a well-known path for storing energy. The hydrogen can then be converted back to power through a fuel cell, or by combustion in a turbine. Hydrogen is not easily stored; and conversion to liquid, or storage at high pressure, requires significant energy. Full round-trip efficiency can be low. Chemical storage of hydrogen through metal hydrides or carbon nanostructures is under intense investigation, but long cycle-life, cost-effective materials are not yet available.

As an alternative, the power-to-gas approach uses electricity to manufacture hydrogen, say by electrolysis, which is then reacted with carbon dioxide at elevated temperature to form methane. The methane is easily stored or pumped directly into the natural gas network. The disadvantage is the low overall energy efficiency, which is common to many of the hydrogen conversion processes.

100 Conway, BE et al. 'The role and utilisation of pseudo-capacitance for energy storage by supercapacitors', *Journal of Power Sources* 66: 1–14.

101 Wu, X et al. 2015 'Dual support system ensuring porous Co-Al hydroxide nanosheets with ultrahigh rate performance and high energy density for supercapacitors', *Advanced Functional Materials* 25: 1648–1655.

Another approach reacts the hydrogen with nitrogen to form ammonia. This compound is easily stored and transported, and is already widely-used in industry at the megatonne scale. The use of ammonia as an energy storage agent in conjunction with solar thermal power generation has been strongly researched at the ANU.[102]

3.5 Opportunities from Australian energy research.

Australia has a surprisingly rich history in energy storage research, development and commercialisation, particularly with batteries and capacitors. This is reflected in many of the examples given above.

» The University of NSW developed the vanadium redox battery, which has been commercialised by Sumitomo and with some recent innovations by UniEnergy in the USA.

» ZBB, in association with Murdoch University, developed the zinc-bromine battery which is now being commercialised by ZBB in the USA and Redflow in Australia.

» The CSIRO developed the carbon-based supercapacitor that has been commercialised by Cap-XX.

» The CSIRO supported much of the lead-acid battery fundamental science during the 1990s and 2000s, and developed the 'Ultrabattery' that has been commercialised by Ecoult.

Currently, research and development into storage technology and devices, and the use and integration of energy storage into energy networks, is very active in Australia. It is now accepted that energy storage is essential for successful integration of renewable energy with the grid, and that and that widespread uptake of storage could be a disruptive influence on Australia's future electricity grid.[103]

Research is needed into the most cost-effective means of utilising the technology, covering areas such as the optimum location, size, operation and effects of storage devices (that is, energy systems research), especially as applied to Australia's energy grids, as well as research into storage devices and technology, such as new materials and better power conversion into and from storage. The US Government, for example, has provided US$185 million for research and demonstration of energy storage (the American Recovery Reinvestment Act, 2009).[104]

Many analysts and commentators predict that energy storage technologies, especially advanced batteries, will show exceptional growth in the next decade. Australia has a great opportunity to use its considerable research base in storage to capture some of this market.

102 Available at http://stg.anu.edu.au/research/storage/ammonia.php

103 Graham, P et al. 2013 'Change and choice: The Future Grid Forum's analysis of Australia's potential electricity pathways to 2050', CSIRO Technical Report.

104 Available at http://www.energy.gov/recovery-act 97 © OECD/IEA 2011 Technology Roadmap Smart Grids, IEA Publishing. Licence: https://www.iea.org/t&c/termsandconditions/#d.en.26167

4 End-use: A network transformed

To design a future energy system that is affordable, secure and sustainable, we need to look beyond the way we generate energy and our capacity to store it. We must also examine what happens next. Once electricity has been generated it must be distributed as efficiently as possible to end users. When it reaches the consumer, be that a household, a business or a utility, it must be wisely and efficiently used. Both these issues pose opportunities and challenges. Both the grid and the consumer need to be smarter.

4.1 Smart grids and network management

Smart grids will have a key enabling role in creating an electricity ecosystem that enhances security, economic development and sustainability. A host of technologies deployed in the grid and by energy consumers will enable information to flow back and forth between suppliers and end users. While the idea of adding 'smarts' seems intuitively simple, its implications are enormous and transformational.

An intelligent network optimises energy distribution between power suppliers and users, utilising sensors and distributed automation. This allows the grid to dynamically manage power supply through the constant evaluation of usage information and needs which can then be appropriately met through both centralised and decentralised generation options, as well as storage and demand management.

What does a smart grid do? **For consumers** it helps moderate their own energy supply and usage to reduce waste, lowering bills and using power in a more sustainable way. **For the electricity industry** it helps prevent outages, shortens response time to problems, reduces cost and boosts efficiency, and allows operators to resolve issues remotely. Major economies are investing large sums into implementing smart grids. Global smart-grid technology investments reached US$45 billion in 2013 (up 35% from 2012), and a cumulative total of US$400 billion will have been spent by 2020, with investment

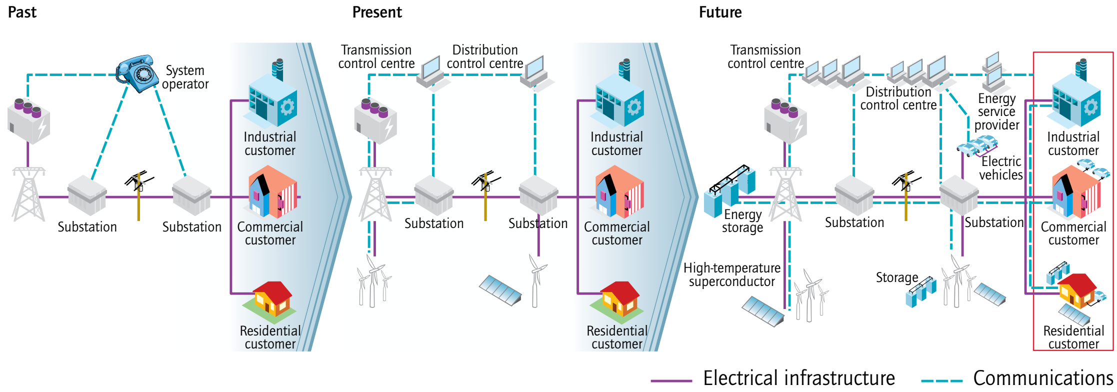

Figure 8: The "smartening" of the electricity system is an evolutionary process, not a one-time event. Source: OECD/IEA 2011 Technology Roadmap Smart Grids, IEA Publishing, France.

growing at an average compound annual rate of over 8%. Technologies range across five main areas: transmission upgrades, substation automation, distribution automation, smart-grid IT and operations technology, and smart meters.[105]

Decentralised expenditure by end-users has the potential to dwarf this direct expenditure. Technologies and devices that can facilitate the smart grid, but will be purchased directly by households and businesses include electric cars, small rooftop PV modules with storage, and remotely or intelligently switchable appliances. The market for these types of devices is expected to increase greatly.

In the European Union, investment is coordinated by a public/private initiative known as the European Technology Platform for the Electricity Networks of the Future (known as ETP SmartGrids) which, since 2005, has coordinated policy and technology research and development.[106] Technologies being used to add 'smarts' to the existing electricity grid include sensors and monitoring to inform decision making about supply and demand, information processing to make decisions, communication to share information as appropriate and to coordinate decision making, and controllers to actually implement desired actions. The evolution of this technology is sketched in Figure 8.

Similar efforts began in the USA in 2007, with the US Department of Energy coordinating national grid modernisation via a Federal Smart Grid Task Force. Its goals are:

- developing self-healing from power disturbance events
- enabling active participation by consumers in demand response
- operating resiliently against physical and cyber attack
- providing power quality for 21st century needs
- accommodating all generation and storage options
- enabling new products, services and markets
- optimising assets and operating efficiently.[107]

Such capabilities can enhance the ability of the existing grid to improve reliability, power quality and overall network economics, while allowing customers to manage their electricity demand and improve their energy efficiency. They can also play a vital role in facilitating the integration of variable and somewhat unpredictable renewable generation and potentially other new clean energy technologies—generation, storage and loads (including, for example, electric vehicles) into the network.

Many of these technologies are already progressing, although at very different speeds across different jurisdictions and without the large-scale, integrated and system-wide demonstrations that will be required to determine and then implement the most valuable smart-grid opportunities.[108]

105 *Global smart grid technologies and growth markets 2013–2020,* GTM Research, Boston, 2013.

106 *Horizon 2020: Work programme 2014–2015,* ETP SmartGrids, April 2015.

107 *The future of the grid: Evolving to meet America's needs,* US Department of Energy, December 2014.

108 *Energy technology perspectives 2014: Harnessing electricity's potential,* International Energy Agency, 2014.

Research trends and applications

Most major jurisdictions have established smart grid roadmaps through collaborative government, industry and research community efforts. These typically include detailed technology R&D and demonstration frameworks to provide a basis for assessing key research needs and establishing research priorities.

The European Union has established smart grid research priorities across broad transmission level and distribution level clusters. The transmission level has a focus on flexible power technologies as well as new methods and tools for network planning and operation, market arrangements and asset management. At the distribution level, the focus extends to the integration of smart customers and distributed generation, and network monitoring and control automation.

Longer-term priorities include more integrated planning and operation tools, advanced forecasting techniques, energy management systems for distributed technologies—generation, storage and customer loads—more flexible transmission network options, energy user ICT infrastructure and, importantly, broader socio-economic 'ecosystem' development in areas including business models, regulation and institutional frameworks.

The need to integrate diverse technologies is arguably the greatest barrier in developing and deploying smart grids. Smart grid research also needs to be integrated with broader research efforts including, particularly, the so-called 'internet of things' and the challenge and opportunities of everything being 'online all the time'. There are obvious synergies with smart grids in the areas of ICT and big data, yet also possible challenges including the growing energy usage of ICT infrastructure (as covered in Chapter 4.2)[109] It is also widely appreciated that the physical, technical, economic, commercial and institutional complexity of our present electricity industry means that commercially-driven R&D, demonstration and deployment by market participants alone will not be of the scale, speed and level of integration that is required. Opportunities exist to improve industry market arrangements and regulation to better support such activities, but it is clear that government research coordination and funding will be required.[110]

Despite a number of trials, Australia has fallen behind in the global drive to modernise its electricity network for the demands of the 21st century. At the same time, substantial efforts to research, coordinate and plan smart grids are racing ahead in jurisdictions including the European Union, Canada, United Kingdom, Ireland, Japan, South Korea and the United States. Australia lacks a coherent and broad innovation framework for smart grids, as well as appropriately-resourced research effort or coordination, while current regulatory and market arrangements are actually hindering commercially-driven progress.[111]

Microgrids and virtual power plants (VPPs)

Microgrids and VPPs are two approaches to meeting customer demands and wider electricity system needs. By aggregating diverse distributed resources, these approaches can undertake wider power-system roles including participation in wholesale electricity markets and the provision of both system and network services necessary for a secure and reliable electricity system.

Microgrids are already widely deployed around the world in remote locations where conventional grid supply is either technically or economically not feasible. Such a microgrid can include diesel and gas generators, hydro, photovoltaic, wind and other generation sources, with load management and potentially associated storage systems to provide grid-quality power to remote communities. Australia has particular expertise in such systems due to the significant number of remote communities both in central Australia and its many small islands.

However, microgrids can also be formed from a section of a large power system that can disconnect from the main grid and operate autonomously for varying periods of time, supplying its own loads from internal power sources at some times, and relying on the main grid at other times. Such microgrids are typically on the scale of a small town, neighbourhood, hospital, university or military base.

A microgrid needs sophisticated control circuitry to implement rules governing its interaction with the wider grid, including how and when to use its storage and automatically isolate from the wider grid when required. Application of machine learning approaches to microgrid control is an active area of research.

109 International Energy Agency, 2014 (op. cit).

110 *Global gaps in clean energy R&D*, International Energy Agency, 2010.

111 *Towards Australia's energy future: The enabling role of smart grids*, Smart Grid Australia, 2014.

When a microgrid is operating without a connection to the central power grid, it is said to be 'islanded'. A microgrid may island itself during an outage or when grid power quality is poor, providing improved reliability and power quality to loads within the microgrid. Islanding allows generators within a microgrid to keep generating during grid outages, which is not permitted on standard grids for safety reasons. A microgrid almost always requires energy storage if it is designed to transition into island mode without temporary loss of power to internal loads.

Microgrids also have the ability to use their local generators, storage and demand management regime to help stabilise its voltage and frequency interactions with the central utilities. If renewable sources are included, their variability can be managed by the microgrid, saving the rest of the power system from having to deal with it. The controller of a microgrid decides which energy resources to use at what times in order to balance load and generation. It may take into account predicted load profiles, predicted power price profiles, predicted wind or solar power profiles, predicted heating or cooling needs and (if the microgrid contains co-generation) emissions, including noise, and other parameters.

Simple microgrids containing one or two diesel or natural gas generators are fairly common in locations where reliability is valued highly, such as at hospitals, military installations and some factories, though historically these installations were referred to as uninterruptable power supplies, not microgrids. The cost of microgrids is generally not considered to outweight the benefits in many areas of Australia that have reliable grid systems, unless the consequence of outages is not acceptable (e.g. hospitals). In areas with less reliable power systems, microgrids may be more easily justified economically. As the cost of maintaining long power interconnects increases, as well as the frequency of extreme weather events, the attractiveness of microgrids increase. Microgrid technology is undergoing significant R&D, and several more complex pilot projects are under way. Japan's New Energy and Industrial Technology Development Organisation has been running large-scale smart grid and microgrid pilot projects in Kyoto, Yokohama, Kitakyushu and Toyota City, east of Nagoya.[112]

More than 400 microgrid projects are under development worldwide, with 219 in North America. Revenue from deployment of microgrids has been estimated at just under US$10 billion in 2013, and is forecast to rise to more than US$40 billion annually by 2020. Navigant Research projected the value of microgrids to exceed US$40 billion per annum by 2020, and noted: "The microgrid market is moving into full-scale commercialisation. Driven by falling costs for solar photovoltaic systems and the easing of prohibitions against the operation of distributed generation assets during times of grid stress, the adoption of microgrids will accelerate as awareness of—and confidence in—the platform's capabilities grow."[113]

Virtual power plants (VPPs) are similar to microgrids in that they are an aggregation of energy resources that can be treated as a single larger resource from the grid operator's perspective. VPPs therefore do not have to be co-located, and could incorporate a wide variety of energy sources from across the geographical area of the grid. A microgrid could be considered a type of VPP capable of operating in island mode and where its components are geographically co-located.

In general a VPP may use any combination of renewable power sources, conventional power sources, energy storage and demand response. A VPP is typically less expensive to implement than a microgrid because it can combine existing infrastructure using software controls rather than control circuitry and intelligent switches. In fact, because VPPs are tied together by software controls, a given VPP may last for only a short length of time (a year, a month or less than a day) and can be easily and inexpensively modified.

An aggregation of renewable resources can also act as VPP, as has been piloted in Europe with the FENIX project,[114] where various small-size generating units have been aggregated to form a 'single virtual generating unit' that can behave as a conventional power station. The International Renewable Energy Agency described the main benefit of this approach:

112 Takada, K 2010 'Microgrid research in Japan & New Mexico project', Vancouver 2010 Symposium on Microgrids, 21 June 2010.

113 Asmus, P 2013 *Microgrids*, Navigant Research.

114 Available at http://www.fenix-project.org/

"*When geographically and technologically diverse renewable resources are grouped together, the reliability of the group is significantly higher—and the variability significantly lower—than that of each individual resource due to aggregation effects.*

Even if a group contains no dispatchable resources, it may still be useful to consider it as a VPP, albeit one that must be treated differently from a conventional power plant.

There are advantages from the utility's perspective in dealing with a single, less variable VPP over dealing with myriad highly-variable individual sources."[115]

CSIRO continue to lead VPP research in Australia.

Modernising Australia's grid

Australia has much to gain from appropriate 'smart grid' research, and much to lose in failing to do so. The Australian electricity sector was once cost competitive, but now has some of the highest commercial and residential prices in the world, and large network expenditure has been a key driver of this change. In addition, the industry's high emissions intensity means that reducing emissions to safer levels will require a far greater industry transition in Australia than in many other countries.

Australia also has some key opportunities. A mass 'smart meter' rollout almost complete in Victoria—and now underway in the other states—provides an excellent basis for research, development, demonstration and deployment of new smart grid options. Already, new technology platforms are emerging, including end-user web portals provided by retailers, as well as mobile apps, to assist in energy management. More than 1.4 million household PV systems have been installed (among the highest per-capita ownership of such systems in the world) and real progress is being made on a range of demand response technologies such as the 'peak smart' air-conditioner program in Queensland.[116]

While only limited smart grid equipment manufacturing (and hence associated R&D) exists in Australia, many of the key research challenges lie in the effective integration of existing technologies. Australia is well placed to be a fast follower and learner in this space: local capabilities in ICT are a key opportunity, both in terms of facilitating the 'smarts' of smart grids, but also managing some of the associated risks including new security threats, such as hacking of systems and cyber-attacks. Australia's vast, and hence expensive, electricity networks (see Figure 9) offer highly cost-effective opportunities for targeted technology deployments.

The potential of smart grids in Australia was noted in the Australian Government's *Energy White Paper* and we have seen a range of government—and industry—supported R&D and demonstration efforts to date. The most notable is the Smart Grid, Smart City project[117] which tested a range of new technologies with actual customers. It involved the CSIRO, Ausgrid, Sydney Water, Hunter Water, the University of Sydney, the University of Newcastle and the municipalities of Newcastle and Lake Macquarie.

The final report in 2014 found that introducing smart grids, together with better tariffs and customer feedback technologies, had the potential to provide more than $27 billion in net benefit to Australia.[118] Other industry stakeholders, notably distribution network service providers, have also been piloting a range of potential smart grid technologies and applications over the past decade. These trials have highlighted both the opportunities yet also challenges of successful widespread smart grid deployment.

4.2 Information and communications technology: Benefits and challenges

The internet and its vast network of interconnected computers, smart devices and phones, servers and data centres underpins most aspects of modern life. It will be an intrinsic part of our future energy system. This information and communications technology (ICT) infrastructure uses a lot of energy itself. The world's ICT infrastructure consumes around 1/20th of global electricity supply, a fraction that is growing rapidly as the capacity and geographical reach of the Internet and the mobile wireless network expands. Balanced against this increasing consumption are a range of energy abatement approaches that can be applied through intelligent and appropriate use of the Internet and other ICT infrastructure.

115 *Smart grids and renewables: A guide for effective deployment*, International Renewable Energy Agency, November 2013

116 *Towards Australia's energy future: The enabling role of smart grids*, Smart Grid Australia, 2014.

117 Available at http://www.smartgridsmartcity.com.au/About-Smart-Grid-Smart-City.aspx

118 *Smart grid, smart city: Shaping Australia's energy future*, Ausgrid, July 2014.

Most of the energy consumption in the Internet is attributable to the so-called *access network*—the connection between telephone exchanges and the home and businesses that they serve. For residential fixed-line networks, the main contributors to this consumption are equipment in the exchanges and the modems in homes. This equipment usually operates 24 hours per day and is under-utilised in low-demand periods: the fixed-line access network consumes around 10 W per home, or about 100 MW for all homes in Australia.

Global efforts to reduce the energy consumption of the access network have concentrated on ideas such as *sleep-mode* operation of home modems (where a modem is switched into a low-power state when no data is flowing) and lower-energy technologies such as *fibre to the premises* (FTTP). Standard, off-the-shelf FTTP access networks consume around half as much power as copper-based access networks, and recent research in Europe shows that advanced FTTP modems could potentially consume an order of magnitude less power than copper-based networks. Organisations such as Green Touch—an international consortium of major ICT companies and researchers—have argued that FTTP is the best long-term technology solution for broadband networks[119].

In cellular wireless networks, most energy is consumed by base stations, with a conventional base station consuming 1 kW or more. Much of this energy is converted into radio frequency (RF) signals that are broadcast across the entire cell area. Only a tiny portion of this RF energy is intercepted by mobile devices, the rest being wasted. As the number of base stations expands in response to rapidly-increasing demand by users for more access to data, the total power consumed across the network increases. Australia's 16,000 bases consume about 40 MW.

Researchers and network operators accept that the current rate of cellular network growth is unsustainable using today's technologies. One solution proposes that large energy-consuming base stations be replaced by a larger number of more energy-efficient smaller base stations serving a smaller number of users; another is to develop base stations with directional antennas that track users and focus radio frequency energy on them, thus reducing the amount of wasted energy.

Figure 9: The transmission infrastructure which makes up the National Electricity Market (NEM) in Australia. Image courtesy Australian Energy Market Operator.

Data centres are the nerve centres of the Internet. Most communications sessions on the Internet either originate or terminate at a data centre. A large modern data centre occupies tens of hectares of land and consumes hundreds of MW of power, so they are obvious targets for further energy efficiency research: techniques include passive cooling; highly energy efficient processors in server equipment combined with virtualisation techniques which improve overall efficiency; and low-power electrical and optical interconnects between racks of equipment.

Another important issue is the growing amount of data that resides on spinning disks in data centres. The power needed to maintain the world's exploding supply of data is growing rapidly, and new lower-power storage technologies will be necessary if the quantity of stored data keeps growing at the current rate. In the longer term, it will likely become necessary to implement protocols and processes for deleting data that is no longer needed.

Home and office ICT equipment account for a significant component of overall ICT energy consumption. Some savings have recently been achieved through improved efficiencies in items such as domestic TV sets and personal computers, but other trends, such as

119 Available at http://www.greentouch.org/

a widespread move towards energy-hungry Internet protocol (IP) telephones in many office buildings, have increased consumption.

ICT can enable energy abatements in other industries: video conferencing can reduce travel, smart building management can improve efficiency in both domestic and commercial buildings, ICT-managed variable-speed motors in manufacturing and smart grids for power transmission can all enhance energy efficiency. The Global e-Sustainability Initiative (GeSI), a collaboration of major global ICT companies and organisations, estimates that ICT-managed buildings alone could cut global greenhouse gas emissions by as much as 17% by 2020—equivalent to more than seven times the emissions from ICT in the same period.[120]

4.3 End-use energy efficiency: The untapped potential

Research in end-use energy efficiency starts from a simple question; how much energy is needed for a particular service, be it lighting an office, supplying hot water, warming a house or manufacturing glass or aluminium. We can then seek the lowest energy pathway to delivering that need.

The price of grid electricity delivered to homes and businesses in Australia has risen dramatically in the past five years, mostly driven by enhancement of the network to handle growing peak demand. In consequence many users have moved toward more efficient appliances and equipment and other strategies to reduce their energy bills.

Consider refrigerators: since 1975, the energy required for a standard refrigerator has fallen from 1,800 kWh per year to around 400 kWh per year today, with further reductions to come. In the USA, more efficient refrigerators alone have reduced electricity demand by 30 GW, comparable to the entire conventional electricity generating capacity of Australia today.[121] This single example shows how greater energy efficiency can massively reduce the need to build expensive new capacity, while also cutting wastage and greenhouse gas emissions.

Such innovation was driven by the US Department of Energy, created in 1977 by the Carter administration to respond to the energy crisis following the 'oil shocks' of the 1970s. The Department of Energy worked with industry to develop efficiency standards for 13 household appliances; these were mandated nationally in 1987.

These efficiency standards have reduced US energy consumption by an estimated 3.6% per year. The Energy Star appliance rating system, a voluntary program created in 1992 to identify and recognise energy efficient products, now annually saves American consumers an estimated US$23 billion a year in energy bills, and avoids 210 million tonnes of greenhouse gas emissions, equivalent to keeping 41 million cars off the road.[122]

Energy efficiency covers an enormous range of activities from the home and office to the factory floor. As such, research in this area is a diffuse activity as end use energy efficiency is often multidisciplinary in nature. There are **four main areas** where energy efficiency research and applications are being pursued today: system design; biomimicry; materials; and smart appliances and equipment.

» **Whole of system design:** If major energy efficiency savings are sought, energy systems should be researched and analysed holistically, rather than segment by segment. Electric motor systems are a good example; more efficient components such as motors, pumps, compressors and fans can improve energy efficiency. Continued research is required in these areas, especially for small-scale equipment. However, in the majority of cases, far greater savings are possible if the whole system is examined and optimised; removal of valves, variable speed drives to vary flow rates, larger duct or pipe diameters, anything that focuses on reducing energy loss or wastage from the whole system.

  In HVAC systems (heating, ventilation and air conditioning) of large commercial buildings, delivery of air and water is often inefficient due to poor duct and pipe design and implementation. More efficient HVAC components are being developed utilising variable speed compressors and fans to enhance performance. Research focusing on delivering 'whole of system' energy savings would enhance the economic bottom line of many Australian industries, businesses and homes.

120 *SMARTer2020*, The Boston Consulting Group for the Global e-Sustainability Initiative, 2012.

121 Risser, R 2011 'The proof is in the pudding: how refrigerator standards have saved consumers billions', Building Technologies Office, US Department of Energy.

122 *The history of energy efficiency*, Alliance Commission on National Energy Efficiency Policy, January 2013.

» **Biomimicry:** Over millions of years, plants and animals have evolved to be very efficient in order to survive. Minimising their energy requirements has been a key mechanism to ensure survival. Human designs and processes can learn much from natural systems. Fans and pumps that mimic naturally-occurring systems, minimising turbulence and friction, can significantly cut energy consumption. Minimising waste and recycling materials (as occurs in natural systems) can deliver not only operational energy savings, but also savings in transport and in embodied energy (the energy consumed by all of the processes associated with the manufacture of a product, from the mining and processing of resources to the manufacturing, transport and product delivery).

Natural systems can produce what they need to survive while relying on what humans would consider 'low grade' or 'low temperature' sources of energy. Termite mounds in the Northern Territory maintain internal temperatures near 31 °C through the use of insulation, thermal storage and ground-based air heat exchange, driven by solar radiation, despite outside temperatures ranging from subzero to over 40 °C.

We are currently nowhere near that sort of efficiency and low energy usage. As the move away from fossil-fuel energy gathers momentum, we will again refocus our attention on low-grade energy sources. For example, we can use aquifers to heat and cool buildings hydronically throughout the year with low energy pumping systems. The challenge is: can this be done with long term reliability and low cost, and deliver thermally-comfortable conditions?

» **Materials:** Energy-efficient materials have a great deal to offer in delivering both lower operational energy systems and lower embodied energy. For example, light emitting diodes (LEDs), based on a variety of semiconductor materials are now demonstrating in the laboratory luminous efficacies and lifetimes that not only exceed conventional lighting sources, but also have the potential to exceed the luminous efficacy of daylight, which is currently the best way to deliver light, with the minimum of heat, into a building.

Advances in materials focused on delivering energy savings is a broad field of research, with application for industry, commerce and home owners. Computing hardware and other electronic systems continue to shrink in size, and therefore in energy demand. More efficient TV and computer screen technologies have emerged rapidly over recent decades, combining enhanced visual clarity with lower energy consumption.

Windows are another active area of research, being the weakest element in the thermal insulation of a building. Australian windows are typically single panes of ordinary glass with aluminium frames. Window materials that limit radiative and conductive heat transfer are under development, as are windows that are 'switchable'—allowing heat and light in in winter and only light in summer, or becoming totally opaque at night.

In a related field, research proceeds actively in seeking better insulating materials (such as vacuum-insulated panels and other advanced insulation systems such as aerogels) for walls, refrigerators, hot water storage systems and similar applications.

» **Smart appliances and equipment:** The revolution in computing power and energy efficiency over the last few decades has delivered a revolution in power electronics, bringing the potential for smarter and more energy efficient appliances. Appliances and equipment under active development will sense when to power down to save energy, turning off appliances that are not needed, as well as self-diagnose energy usage and failures. The advent of low-cost sensing, electronics and communications promises appliances and equipment that are increasingly able to inform home and equipment owners of their energy performance and other parameters.

The explosion of data brings great potential for users to better understand and manage energy usage. However, there needs to be more research to develop better information systems that allow home owners and businesses to effectively interact with their energy systems without being overwhelmed with data. Smart systems will be able not only to save energy but to self-diagnose when failures occur, and to take advantage of renewable energy generated on site to minimise the purchase of energy from the grid, so minimising energy costs, peak demand and carbon dioxide emissions.

Competitive pressure and market realities

It is important for Australia to remain competitive in end-use energy efficiency research, especially as it applies to local conditions. Greater research and uptake by industry leads to greater awareness and wider uptake, with direct benefits to local industry and consumers. Government efficiency programs such as MEPS (Minimum Energy Performance Standards)—which establish standards that products must meet or exceed before being allowed to be sold in Australia—improve the bottom end of the market so that the average efficiency of products improves over time.

Energy standards that are aligned to world's best practice benefit all Australian consumers. Otherwise, cheap, low-efficiency appliances and equipment the rest of the world does not want could end up in Australia. Rising utility prices for electricity and gas make end-use efficiency increasingly important. Such efficiency offers Australian users the lowest cost pathway in reducing their energy bills, as well as leading to reduced carbon dioxide emissions and the maximum fraction of energy demand met by renewable sources.

End-use energy efficiency research, by its very nature, is strongly focused on delivering practical, real-world applications. Australian homes, businesses and industry will all benefit from enhancements in end-use energy efficiency that can deliver the same or better services at lower economic and environmental cost.

4.4 Sustainable built environment: Lower costs and healthier lives

Existing buildings account for about 40% of the world's total primary energy consumption, and 24% of carbon dioxide emissions.[123] In Australia, buildings account for a lower proportion of consumption (19%), but as Figure 10 illustrates, are responsible for an equal amount of greenhouse gas emissions: 23%.[124]

Hence, the built environment—detached and attached dwellings, offices, factories, hospitals and education facilities—presents significant opportunities for reductions in both energy use and emissions. Harvesting this 'low hanging fruit' requires a holistic approach to good design and planning of buildings and cities, as well as to all infrastructure that supports them. It requires technologies, tools, techniques, materials and systems that assist in delivering lower-carbon, energy-efficient results.

Reducing electricity demand is perhaps the area of greatest opportunity in the built environment, as it not only avoids generation and supply costs but reduces the engineering requirements—and hence cost—of generation and supply infrastructure. Research challenges remain relevant for both green field developments and retrofitting existing buildings.

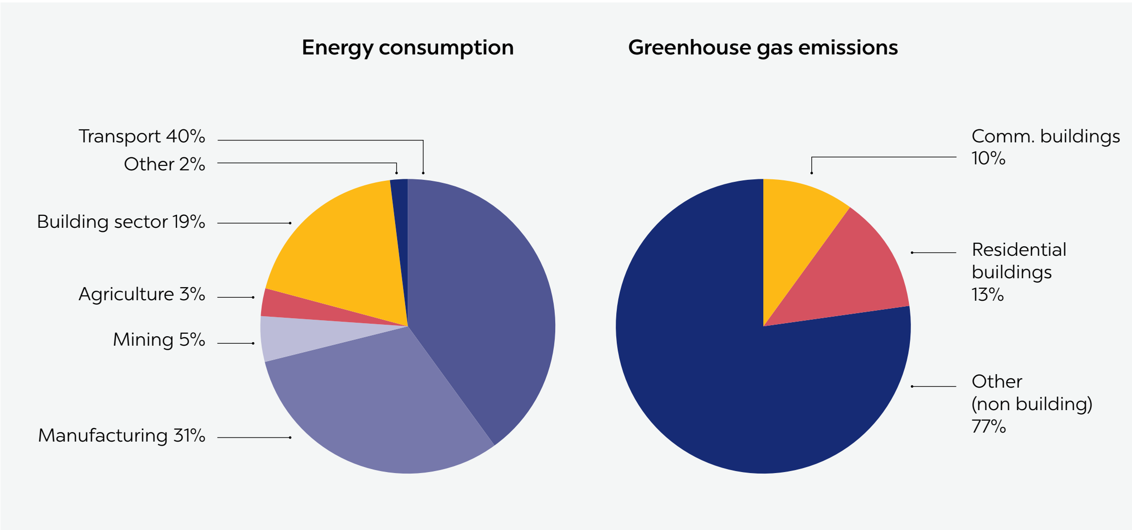

Figure 10: In Australia, buildings consume 19% of energy production and are responsible for about the same amount of greenhouse gas emissions (23%). Image courtesy The Centre for International Economics.

123 International Energy Agency, *2013. Modernising building energy codes.*.

124 The Centre for International Economics, 2007. *Capitalising on the building sector's potential to lessen the costs of a broad based GHG emissions cut. Sydney.*

Figure 11: Energy-positive house in WA. Image courtesy Joel Barbitta at D-Max Photography © Josh Byrne and Associates

In addition to demand-side efficiencies, there are opportunities for 'greener' supply options for energy in the form of larger centralised facilities, or the growing use of decentralised systems. In the latter case, buildings and cities become responsible for a growing amount of their energy, water, waste (and even materials) by reducing, reusing, recycling and regeneration. A high level of efficiency in energy use and sustainable supply do not just minimise the impact on natural systems, but also help reduce the cost burden on end users, as well as governments and utilities, by avoiding the need to build expensive new capacity.

The challenges for researchers in the field is to develop technologies, tools, materials and systems that make it easier for designers and planners to deliver on built outcomes. With the world moving toward a low carbon future, opportunities exist to create a globally competitive industry that specialises in built environment efficiency through high quality collaborative and industry relevant research.

Design and planning innovation

The built environment offers significant opportunity for simple, clever, passive, low-to-zero-energy buildings and precincts by utilising 'climate responsive' approaches. Tools and techniques are widely available, and have been well researched and documented in Australia, but are not yet mainstream among planners and designers. In all buildings, a clever use of elements (building fabric, placement of thermal mass, insulation, glass and shading, natural ventilation and lighting, orientation to the sun and prevailing winds) can produce dramatic reductions in purchased energy use, often to zero (see Figure 11).

In addition to comfort—thermal, visual, acoustic and air quality—good design brings other health and wellbeing benefits. Urban planning that allows for walking and cycling is correlated with improved health and measurable reductions in government health expenditure. The practice of 'biomimicry' in design can deliver significant health and wellbeing impacts, as it relies on high levels of daylight, natural ventilation and visual amenity. In hospitals, faster healing has been measured where rooms are close to trees and natural systems.

Reducing the embodied carbon in building materials requires informed choices during design and construction. Much research is underway on alternative building materials: geo-polymer as a concrete replacement, recycled steel and glass, and other products such as cladding and flooring systems from waste. Research on process stage energy/carbon reduction is also finding new ways to use waste plastics and other materials to replace high carbon-intensity coal in manufacturing. The use of innovative applications of thermal storage based on phase change materials to stabilise indoor air temperatures is also finding new applications in different building types.

System integration

In most building types, passive design alone cannot provide year-round comfort: heating, cooling, lighting, ventilation and fans, pumping and transportation are all needed, and research in these areas is generating ongoing improvements. However, effective integration is very important in whole-of-system optimisation. Very advanced simulation and optimisation software tools (for example, EnergyPlus, ESPr, TAS, Buniup, Accurate) allow engineers and architects (as well as researchers) to model energy and water use, or lighting and passive cooling in buildings and so ensure efficient design integration.[125]

For truly effective efficiency design, all opportunities for efficiency and integration (with architectural as well as engineering systems) must be considered before energy supply decisions are made. Onsite renewables—such as photovoltaics, solar thermal, ground-coupled heating and cooling—provide high-value supply options with low carbon content. Research and development underway in these areas is examining efficiency improvements, cost reductions and integration benefits. Research on next-generation building products with integrated photovoltaic and photovoltaic-thermal hybrid solar collectors (the latter converting solar radiation into both thermal and electrical energy) is exploring how photovoltaic technologies might cover a whole building with appropriate materials to extract energy and at the same time capture waste heat to provide heating and cooling services.

Figure 12: The 'Six Green Star' rated Tyree Building, UNSW. Image courtesy SPREE, UNSW

The Tyree Energy Technology Building at the University of NSW demonstrates system integration incorporating multiple technologies which deliver a 'Six Green Star' rated building (see Figure 12). Green Stars, a voluntary sustainability rating system for buildings in Australia, was launched in 2003 by the Green Building Council of Australia and has helped improve whole-of-building performance around key sustainability indicators.[126]

Research consistently shows a significant correlation between a 'greener' office building, the quality of its indoor environment, occupant perceptions about the workplace and improved productivity. This generates a strong business case for greener buildings, since occupant salaries are by far the largest life-cycle cost for an office building (close to 80%).

If we move from single buildings to considering precincts or urban-scale developments, additional challenges arise for design and planning, including issues of sustainable supply of energy and water, waste management and transport options. Site-wide thinking allows for decentralised energy, water and waste options to be considered in a more holistic way, coupled with storage options and ICT technologies that allow users to better manage demand and supply. However, these are still emerging and require much more research before they can be mainstreamed.

'Precinct information models' for Australian conditions are still in the research stage, and better design and integration at this scale will be available in the future. Central Park, an urban development project in Broadway on the edge of Sydney's central business district, well illustrates current efforts.[127] The six-hectare, $2 billion development on the site of the former Carlton and United Brewery features apartments, offices, shops and cafés, an on-site tri-generation system for power, heating and cooling, and rainwater capture and re-use. A sustainable built environment is mixed with key urban planning aims such as mixed density development, transport and other infrastructure needs of the city.

125 EnergyPlus was developed by the US Department of Energy to encourage greater efficiency in building design, and the Department continues to support and develop the system.

126 Available at http://www.gbca.org.au/

127 Available at http://www.centralparksydney.com/explore/a-sustainable-habitat

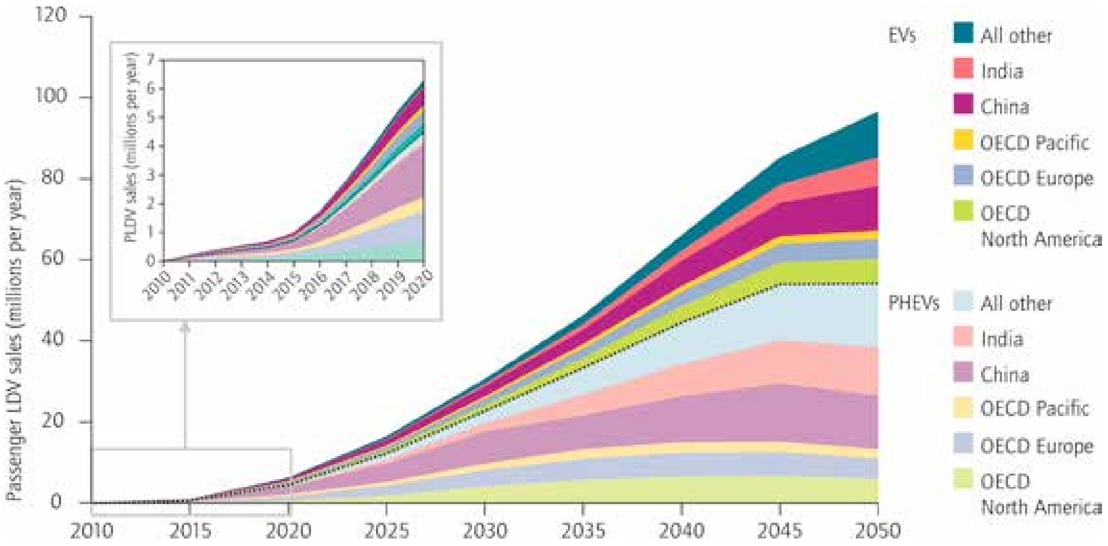

Figure 13: Deployment of electric vehicles and plug-in hybrid electric vehicles. Source: IEA/OECD 2011. Image courtesy © IEA/OECD.

Creating a sustainable city, a liveable environment that improves its population's wellbeing and allows other creatures to co-exist, requires more than good science, engineering and design. It also requires good policy and governance. Informed and engaged communities play a role; we often find strong support among city dwellers for sustainable living approaches. Nevertheless, significant research is also needed in social behaviour change to provide an evidence base for good policy decisions. In this area science, engineering, design, planning, business, governance and social research all interact. A collaborative approach is the best way to explore sustainability opportunities that ensure Australian industry and professions can be globally competitive.

4.5 Electric vehicles: Distributed network for load and storage

Plug-in electric vehicles—both electric-only (PEVs) and petrol–electric hybrids (PHEVs)—are expected to become much more common in the years ahead. Uptake is rising strongly (see Figure 13), although from a low base, despite being more expensive than equivalent internal combustion engine vehicles, with the dominant component being EV battery costs. These are expected to fall in the coming decade, through technical innovation and manufacturing scale. Australia is expected to be a slow follower of EV adoption, although the possibility of sharp increases in oil prices, or sharp falls in EV costs, or both, could alter this.

The *BP Energy Outlook 2035* report[128],published in January 2014, estimates that by 2035 EVs and hybrids will dominate vehicle sales in the developed world, representing 74% of all sales (full hybrids 23%, 'mild hybrids'—with minor electrical role—44%, and plug-in EVs 7%) compared to 26% for conventional ICE vehicles.

Like traditional vehicles, EVs will likely be parked more than 90% of the time, typically at home or the workplace, providing an opportunity to utilise their on-board energy storage to support the grid. While the car is parked and connected to a charging point, energy can be withdrawn from the battery and injected into the electricity network, as is done with surplus energy from residential solar PV panels. In such a scenario, a smart grid is essential.

In principle, the collective capacity of EV batteries could be used to re-phase demand and stabilize the grid. EVs can accept surplus power during times of high generation or low demand, and to feed power back to the grid during peak times. Negotiating workable arrangements with EV owners, including pricing and how to guarantee sufficient levels of charge for mobility use, remains a challenge.

While such a vehicle-to-grid (V2G) scenario is technically feasible, the widespread uptake of EVs has a number of technical, metering and regulatory barriers that need to be overcome:

» **standardised communication and control systems**, so that network operators could determine the available V2G capacity in a given region and provide a signal to vehicles

128 Available at http://www.bp.com/content/dam/bp/pdf/Energy-economics/Energy-Outlook/Energy_Outlook_2035_booklet.pdf

to discharge at a given rate and duration. These systems would need to be uniform across all models and makes of EVs, and incorporated into the charging points

» **sufficient vehicles** and infrastructure available to provide a useful service

» **a metering and billing system** that manages payments and charges between the vehicle owner and the network service provider or other users of the service

» **a regulatory framework** that provides support for all stakeholders and a market that provides appropriate value to all stakeholders

» **a willingness** from EV manufacturers and battery suppliers to allow V2G use without affecting vehicle and/or battery warranty.

EVs also have the potential to affect future electricity demand: it is estimated that EV ownership may increase an average annual Australian household's electricity consumption by up to 40%, from 6–7 MWh to 8.7–9.7 MWh.[129] However, compared to other household power loads (such as air-conditioning), even under a high EV adoption and growth scenario, it is unlikely EVs will represent an unmanageable load at the transmission level. Were EV charging to occur in parts of the grid lacking the capacity 'headroom' to cope with the extra demand, then there are two options: a) boost the amount of generation, transmission and distribution infrastructure to add capacity; or b) install distributed generation and storage downstream from congestion points to serve the added on-peak demand locally.

129 Vassallo, AM et al. 2014 'The potential influence of electric vehicles on the transmission network serving Sydney', Clean Energy Research Cluster, University of Sydney.

Conclusions and recommendations

Energy production and use, particularly electricity, underpins every sector of Australia's economy and society. Australia's vast energy resources, including abundant renewable sources as well as fossil fuels and uranium, mean that energy security can be maintained into the future. The sustainability and affordability of the energy supply options that Australia choses, however, will substantially influence our quality of life.

Technology is rapidly disrupting conventional energy systems both within Australia and globally. Some developments, such as photovoltaics, high-temperature fuel cells and battery storage, have been led or significantly contributed to by Australian research. These changes have profound impacts on the political, institutional, financial and ownership structures of energy systems. Future energy systems will be complex and interconnected, relying increasingly on local energy resources, fit-for-purpose energy conversion and smart control and communications technology.

The future energy system is likely to be far more diverse than the current one. Major trends include:

- increasingly efficient appliances, demand management and energy service delivery
- diversification of energy supply, with a much larger portion from renewable sources
- rapid uptake of distributed energy technologies, including energy storage
- new large-scale generation options, such as wind, solar thermal and geothermal
- electrified transport systems.

Australia has major energy resources of many kinds, scientific expertise in many of the relevant areas and a significant opportunity to contribute in the development and deployment of innovative energy technologies and systems in response to these trends and challenges.

In the decades ahead, Australian consumers, governments and utilities will spend many billions of dollars upgrading and renewing the nation's electricity ecosystem. New energy infrastructure will be built, and coordinated strategies must be developed at a national level to guide investment in technologies, and to facilitate innovation and entrepreneurship. Only by developing long-term strategies that take advantage of new and emerging technologies will the benefits to consumers, industry and the economy be maximised.

Scientific input will be crucial both to the continued development of these new technologies and to the resolution of new problems as they emerge. These include variability of renewable energy supply, much more complex grid management, new types of grids, and increasing consumer interaction with and control of energy systems. Australia is well placed to benefit from the high value-add of the new energy technologies and systems, but this is a highly competitive area internationally and strategic goals will need to be set if Australia is to capture some of the new opportunities.

Recommendations

1. Australia presently hosts a wide range of energy research programs and projects, some of them world-leading. Many Australian universities, as well as the CSIRO, have established energy research centres with strong expertise. While some of this research is indirectly influenced by the annual priorities of research funding agencies, much is being undertaken in the absence of overarching Australian goals, strategic directions or coordination. Past support for energy science and technology in this country has been 'stop-start', with much good work done by Australian researchers being lost overseas, not pursued or abandoned as government priorities changed.

   To address these shortcomings **we recommend** the urgent development of mechanisms to link these diverse efforts through an overarching **National Energy Research Institute**. This would facilitate cooperative research, equipment sharing and the achievement of strategic long-term goals, maximising new energy sector opportunities and ensuring that benefits flow to Australia.

Long-term, tri-partisan funding commitments would allow Australia to compete on the world stage against institutions such as the German Fraunhofer Institutes, the US National Renewable Energy Laboratory, or the Japanese New Energy Development Organisation, all of which leverage long-term government funding and work with industry to develop new energy technologies and to solve new and existing energy problems.

Such a National Energy Research Institute should be accompanied by specific support for industry R&D relevant to new energy systems. This link to commercial markets will be vital to successful innovation in this field as it has been in the coal, gas and petroleum sectors.

2. Australia's electrical energy institutions, structures and associated policy frameworks are now a greater barrier to new technology development and uptake than technology performance or cost. The National Electricity Market was designed in the 1990s and is struggling to respond to the rapid changes in energy technologies and end-use behaviour. To a significant extent it is the victim of 'technology lock-in': technological choices taken in previous decades are now so deeply embedded that they constitute an impediment to innovation and the implementation of new and more appropriate solutions.

   We recommend that **new energy market structures** be examined and implemented so that Australia can continue to gain maximum benefit from current and future technology changes, many of which are rapid. Institutional structures should be flexible and technology agnostic, since we do not know which of the new technologies will ultimately be most successful.

3. Energy management, control and communication technologies will be vital to successful development of the diverse, interconnected energy systems of the future.

   We recommend that **Australia builds on its information technology, communications and electronic control expertise** to develop platforms for our own use (and the use of other nations) as global energy systems are upgraded and enhanced. This would parallel what has been achieved with Wi-Fi innovation in the telecommunications sector.

4. Australia has a key role to play in our region, where energy supply and cost is a major contributor and often a limiting factor in economic, environmental and social development.

   We recommend that Australia places a high priority on **working with our neighbours to develop new energy systems** and to help solve their energy problems, since this has, *inter alia*, strategic security implications for Australia.

Appendix 1:
Expert Working Group Membership

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