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White Paper

Scaling Technologies to Decarbonize Energy

October 2015

World Economic Forum White Paper
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By the Global Agenda Council on Decarbonizing Energy

Abstract

Accelerating the development and deployment of technologies to decarbonize energy will be at the core of tackling climate change effectively at the speed required. The Global Agenda Council on Decarbonizing Energy is a global group of experts convened within the World Economic Forum's Network of Global Agenda Councils for the 2015/2016 term. Mandated to identify effective pathways to decarbonizing the energy mix and catalyse their implementation, the group is focusing on highlighting and accelerating the deployment of technologies that hold significant potential to reduce greenhouse gas emissions from the energy sector. This paper presents the interim findings, including a set of high-potential technologies and pathways to scale. This is not a scientific study or an exhaustive list of high-potential technologies. Rather, it highlights solutions built on expert opinions emanating from the Global Agenda Council. In the coming months, the Council will focus on a few areas highlighted in this paper.

Contributors

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Contents

1. Technologies to Decarbonize Energy Will Be at the Core of Tackling Climate Change

Reducing the greenhouse gas (GHG) footprint of energy value chains is at the heart of success or failure in tackling climate change. The focus of this working paper is not on the overall political climate process, which at the time of writing is gearing up for the COP21 summit, nor is it on companies' actions on climate change, although both are important factors. This paper is centred on how to help further accelerate the global deployment of the technologies that have high potential to decarbonize energy.

Why does this matter? With the consumption and production of energy representing around two-thirds of GHG emissions globally, addressing climate change necessarily involves solutions to energy decarbonization and the more efficient use of energy. Despite astonishing progress on technologies such as solar, wind and energy efficiency, the world is not yet on track to "clock in" within the two-degree Celsius temperature rise that the Intergovernmental Panel on Climate Change, in its fifth assessment report, indicates is the maximum allowable to avoid the most serious consequences of climate change. Faster, wider and deeper action is required to decarbonize energy.

It requires the widespread deployment of technologies that are market-ready today along with the development of new technologies and solutions.

"While energy business as usual" will not suffice to contain climate change, there are several reasons why there is no quick fix. One is trade-offs: energy policy and investments must not only deliver on sustainability but also on the affordability of energy as well as its access and security of supply. A second is scale and time lag: energy infrastructure is capital intensive and typically lasts for several decades, so existing infrastructure and investments today set the path for decades to come. Indeed, the International Energy Agency estimates that 80% of allowable emissions to 2030 are already "locked in" to our existing capital stock [IEA *World Energy Outlook 2014*] – and yet over 20% of the global population does not have access to electricity. A third is the speed of innovation: the typical innovation cycle in energy technology from idea to large-scale implementation takes time, often decades, which reinforces the dominance of incumbent fuels and technologies. The speed of innovation and deployment is increasing but the change to lower-carbon energy systems will inevitably be a long-term transition.

Influencing this transition is both critical and possible. The three key areas of opportunity are:

- Renewable and lower-carbon energy must be deployed more broadly to increase, significantly, their contribution to the global energy mix.
- Solutions for increased energy efficiency and energy conservation, especially in major use sectors such as industry, buildings and transportation, must be adopted more widely.
- Sustainable, clean and affordable energy solutions must be found and delivered to low-income households and the 1.5 billion people without access to electricity.

2. Business as Usual Will Not Be Sufficient – But Progress Made in Recent Years Can Be Built Upon

Over the past 10 years, astonishing growth has taken place in the deployment of certain renewable energy sources, notably solar and wind. Renewable power consumption (excluding hydropower) grew by 12% in 2014, or 42.5% of the growth in global power generation in 2014, representing 28% of world energy growth.[1] This was the 11th consecutive year of double-digit growth in renewable energy. A step change in energy efficiency has also been achieved in some countries. A blend of factors explains this progress:

- Absent a global carbon price, government and regulatory support in terms of targets, subsidies such as feed-in tariffs, green certificates, carbon markets, investment support and tax credits, etc., has contributed to creating real market opportunities and shifting the investor risk/reward for renewables in many countries, attracting more and new sources of capital.
- This has in turn nurtured a virtuous circle where significant R&D and investments by the private sector have taken solar and wind rapidly down the cost curve and expanded their market share.
- At the same time, more open global and regional trade has helped to create global markets for solar, wind and other clean energy technologies.

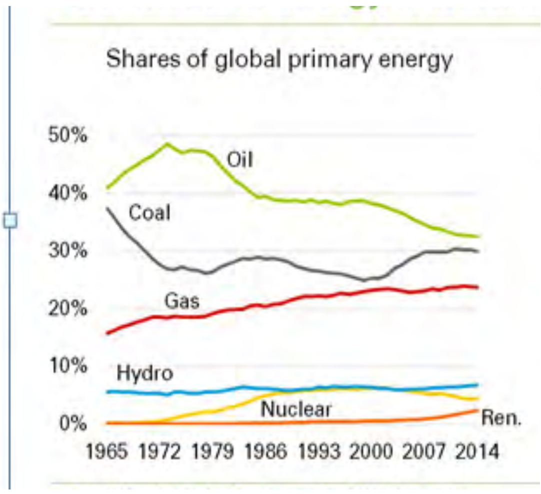
- More energy-efficient technologies have been implemented in many markets, driven by performance standards and regulation (e.g. EU efficiency directives, Corporate Average Fuel Economy (CAFÉ) standards in the United States or the “Toprunner” programme in Japan).
- In North America, the breakthroughs on unconventional gas have enabled a large-scale shift from coal to gas in the power mix, lowering US GHG emissions back to 1990 levels.

These developments prove the power of markets to drive change through investments when the business case for lower-carbon energy is attractive. But more is needed and can be done. Despite this rapid growth, renewables (excluding hydropower and nuclear energy) provided only around 3% of the world’s energy needs and 6% of the world’s electricity in 2014.[2] Regulation has not always favoured the most effective investments in terms of cost of carbon emission reduction (indeed in some cases it has generated perverse incentives to increase emissions), nor has it unlocked low-carbon energy solutions at a speed and scale commensurate to the climate challenge.

One example of inefficiency is the market fragmentation created by national versus regional targets and policies. A recent study by the World Economic Forum estimates that Europe could have saved up to $140 billion if deployment of renewables had been optimized within and across borders.[3] Many countries do not have policies to incentivize lower-carbon solutions and most carbon markets today have not yet fully succeeded in providing a sufficient price signal to drive investments and innovation. Trade barriers still exist for clean energy technologies despite free trade progress.

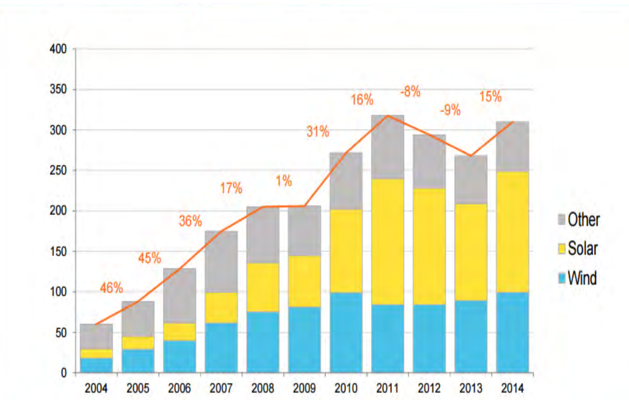
While solar, wind and energy efficiency are among the areas that have progressed fast, other technologies to decarbonize energy, including carbon capture and sequestration (CCS), advanced nuclear and advanced biofuels, have seen less progress and largely remain untapped opportunities.

Figure 1: Shares of Global Primary Energy



Source: BP Statistical Review of World Energy 2015

Figure 2: New Investments in Clean Energy, 2004-2014 (US$ billion)



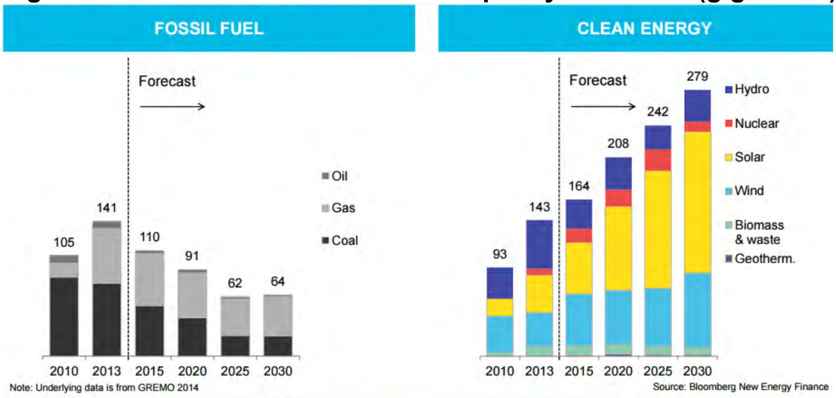
Source: Bloomberg New Energy Finance Summit 2015

3. What Are High-Potential Technologies and Solutions?

Unsurprisingly, there is no “silver bullet” technology or solution to decarbonize energy: it requires a range of technologies that can be deployed at competitive costs according to market opportunities, country preferences and legacy infrastructure. Naturally, the system costs and value of different technologies are also factors to consider and will differ according to contexts in different countries. However, an analysis of the system costs and value goes beyond the scope of this paper.

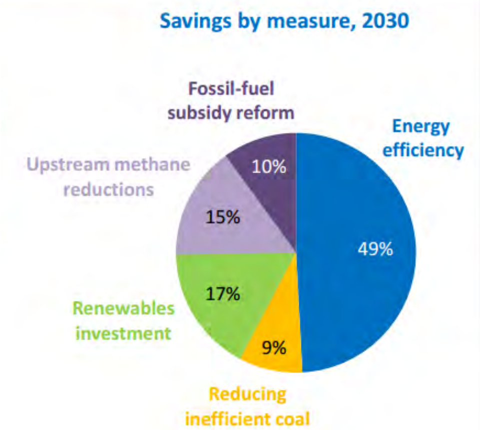
Some technologies today are at a mature stage, attracting high levels of investment, although they still have significant potential for growth and further cost reduction. Others are at the stage where more basic research, applied R&D or pilot testing are needed to take them to maturity and reach the “market tipping point” where investments will unlock larger potential.

Figure 3: Global Power Generation Capacity Additions (gigawatts), 2010-2030 Forecast



Source: Bloomberg New Energy Finance

Figure 4: Energy-Related GHG Emission Savings Potential by Source, to 2030



Source: International Energy Agency, *World Energy Outlook Special Report 2015: Energy and Climate Change*

A crystal ball to predict how fast various technologies will scale hardly exists. But uncertainty does not prevent the acceleration of developments. The Global Agenda Council on Decarbonizing Energy does not aim to produce scenarios – many already exist, as those illustrated in Figures 3 and 4. Rather, the Council has formed an opinion on the technology that holds the greatest potential for decarbonizing energy in the time frame up to 2050 if properly enabled over the next 15 years. The technologies were assessed based on:

- Decarbonization potential
- Feasibility and scalability
- Costs and affordability
- Potential accelerators and enablers

The methodology used was not scientific. Instead it was based on the opinions of the experts in the Global Agenda Council and discussions within the group. The technologies examined have been grouped as "short-term solutions" – market-ready for accelerated deployment in the next 5 years – and "medium-term solutions" – not yet market-ready but with significant potential for acceleration and deployment in a 5- to 15-year time frame. This overview of technologies cannot be exhaustive; the Council members certainly recognize there will be other high-potential technologies and solutions and the group is not attempting to pick winners.

The Council has chosen to take the perspective of 15 years because the challenge is urgent and actions taken within this time frame are likely to have major effects in the coming years and decades. At the end of the transformation process, the energy system must in effect be fully decarbonized. During the transformation, efficient carbon-based technologies will still be used, but they will need to be phased out by 2050, so the impact of stranded assets and wasted investment must be part of any economic assessment.

A summary of the 15 high-potential short- and medium-term technologies the Global Agenda Council has identified is featured in Box 1, in no particular order. Each technology is described more extensively in the technology overview section of this document, together with a discussion of the related enablers and application areas.

Box 1: 15 High-potential Technologies to Accelerate

Short-term technologies (0-5 year horizon for acceleration, in no particular order)
1. Solar-PV
2. Wind power
3. Third generation nuclear energy
4. Ultra-supercritical steam cycle coal carbon capture and sequestration replacing less efficient coal plants
5. Energy efficiency in buildings
6. Energy efficiency in transportation
7. Efficient industry processes

Medium-term technologies (5-15 year horizon of acceleration, in no particular order)
1. Advanced power storage
2. Carbon scrubbing technologies (CCS and CCU)
3. Advanced nuclear reactors
4. Next generation power electronics
5. Next generation biofuels
6. Hydrogen technology
7. Advanced geothermal
8. Ocean energy

4. Pushing the Boundaries of Technology Requires Attention to Enablers

Under the right conditions, both the speed of innovation and the deployment of technologies to decarbonize energy can be accelerated substantially in relation to “business as usual”. Each technology will have different market opportunities, which can change over time as energy markets, policies and the costs of the technologies themselves change.

A mix of enablers will be needed to accelerate technologies, and different enablers can be more effective than others in accelerating a given technology. Some enablers – such as pricing carbon – will have a positive impact across all technologies but will not be sufficient to unlock all high-potential solutions. The Global Agenda Council has considered which enablers are most suited to unlock different technologies (highlighted in the technology overviews). They fall into six categories, described in Box 2. Box 3 maps the enablers with the technologies.

To minimize the overall GHG abatement costs and the costs of energy, carbon and energy market mechanisms must enable companies to optimize investments across geographies and technologies to pursue the best opportunities. In terms of policy, this means that regional, and to the extent possible, global coherent frameworks are better than a myriad of different national schemes. It also means that mechanisms for crediting carbon reduction from measures taken abroad can lower the costs of GHG reduction and increase market opportunities for low-carbon energy technologies compared to a situation without international carbon credits. This will obviously need to be balanced with the fact that opportunities to reduce GHG emissions from energy exist in all countries.

Box 2: Enablers to Accelerate Development and Deployment

1. Sending a strong price signal for carbon
A substantial price signal for carbon across geographies and sources of carbon emissions will have the effect of internalizing the climate impacts in investment decisions and consumption choices. This will boost the market appetite for lower-carbon energy solutions and thus have a beneficial impact across the range of technologies. A carbon price – through a carbon market or tax – will stimulate further deployment of market-ready technologies. The price of carbon will need to be set at a level that has a real impact on decisions and, to the extent possible, it will need to be both global and universal to avoid "carbon leakage", for example through industries moving production to countries with low or no price signal. Absent a global price for carbon, government and regulatory support in terms of targets, subsidies such as feed-in tariffs, green certificates, national carbon markets, investment support and tax credits can create a market push for low-carbon energy technologies.

2. Stimulating government investment, innovation and public-private partnerships
Some technologies, such as advanced nuclear, ocean energy and CCS, are not yet mature; further innovation and testing is needed before they are market-ready at affordable prices. Companies will play a key role in driving innovation but will not always have sufficient incentive, funding or authority to deliver market-ready solutions. In areas like CCS and advanced nuclear, companies on their own will struggle to fund pilot projects and appropriate test beds and to take on all the legal liabilities associated with the large-scale testing needed to help these solutions mature. A special opportunity therefore lies in public-private partnerships that can further the development of technology and fund pilots. This can be done nationally – some governments have noteworthy energy innovation programmes – although for the most part government financial investment in innovative technologies is neither significant nor well joined up internationally. There is considerable scope for more government investment and greater international collaboration and public-private cooperation, to pool resources and share risks among "coalitions of interested parties". Higher levels of government investment and collaboration can send positive signals to markets, catalyse public-private collaboration and concretely underpin government rhetoric on climate action.

3. Raising performance standards and enabling competitive markets
Energy efficiency standards and the labelling of consumer goods, transportation and buildings have proven to be particularly effective in stimulating energy-efficient solutions. The CAFÉ fuel standards in the US and the average fleet fuel efficiency standards in Europe have accelerated innovation among auto manufacturers. The Japanese Toprunner programme is an example of how stretching future performance standards can drive technological development to save energy. The energy efficiency labelling of cars, buildings and consumer appliances has also played a part in informing consumers and in lowering the energy intensity of global growth. Efficient LED light bulbs have become the norm in many countries. Broadening the use of performance standards in countries where this is not yet common as well as innovating in smart performance standards that nudge consumers to save energy and companies to innovate can have strong impact. When crafting performance standards, policy-makers also need to consider enabling rather than stifling innovation and must be careful not to pick specific "technology winners" to benefit from the power of competition.

4. Facilitating behavioural change, public awareness and technological adoption
Consumers across the world are growing increasingly aware of the risks of climate change and many are seeking ways to contribute through consumption behaviour or by installing distributed renewable energy, such as heat pumps and rooftop solar panels. In addition to sustainability concerns, such consumer behaviour can also be economically motivated and nudged. Public and private information campaigns, energy service companies and smart business models to overcome investment and financing challenges for distributed low-carbon energy or to offset personal GHG emissions are enablers that can increase public awareness and facilitate behavioural change. Carbon emission and energy efficiency labelling as already stated are important also.

5. Lowering barriers to trade and investment in low-carbon and energy-efficient technologies
To enable efficient global value chains and lowest cost deployment of low-carbon energy technologies, trade and investment policies must be supportive. The cost of capital for renewable energy investments is commensurate with the risk and can often be substantially higher in developing countries than in developed countries. National policies, legal safeguards and international financing mechanisms that reduce the risks and therefore lower the cost of capital investments in low-carbon energy technologies can boost investments. Trade facilitation can also contribute through eliminating

or reducing tariff and non-tariff barriers to international trade in low-carbon energy. The efficient classification of environmental goods is crucial for trade facilitation of these technologies. The Sustainable Energy Trade Initiative Alliance is one coalition working to enable the development and deployment of clean energy technologies through free trade. As new global and regional bilateral trade agreements are created, the options to create freer trade of low-carbon energy technologies need to be considered and included.

6. Planning smarter infrastructure

A lot of energy is wasted through inefficient transportation and industrial processes, lack of electricity grid infrastructure or inefficient city design. Smarter city designs and solutions, such as congestion charging, real time congestion information and the expansion of public transportation, can enable substantial reductions in energy consumption. Facilitating electric mobility and soft mobility such as cycling has great potential in cities with high population densities. Distributed energy from renewable sources, such as rooftop solar, district heating and cooling and combined heat and power, waste to energy, etc., can enable cities to contain the GHG impact of energy. The digitization of energy systems, smart meters and more integrated smart grid solutions that optimize demand and supply, including also distributed sources, can further enable the more efficient use of energy among industrial and private consumer of energy, as well as the better use of low-carbon energy from distributed sources.

Since projected growth in energy consumption and GHG emissions is largely dominated by major emerging economies, it is crucial to enable solutions suitable also for these markets – not only for mature economies. The biggest emerging economy – China – has already taken a leading position in renewable energy deployment, with considerable further opportunity for the deployment of low-carbon technologies to meet the growing demand and the country's climate and energy goals. India – another major emerging economy – is also bound to invest in new energy capacity as it has a significant number of people without access to electricity today. Enabling suitable and affordable low-carbon solutions to fill these needs, such as efficient LED lighting powered by solar panels instead of traditional incandescent light bulbs and diesel generators, can make a real difference in India and other countries with energy access issues.

Box 3: Potential Accelerators and Enablers for Market Introduction or Increase

Technologies	Box 3: Potential Accelerators and Enablers to market introduction or scale up					
Short term (0-5 years)	Strong Carbon price signal	Government Investment and Public private partnership	Raising performance standards and enabling competitive market	Facilitating behavioral change and technology adoption	Lowering barriers to trade and investment in low carbon technologies	Smarter infrastructure planning
Solar PV	■■■	■■		■		■■
Wind power	■■■			■	■■	■■
Third Generation Nuclear Energy	■■	■		■	■	
Ultra Supercritical Steam Cycle Coal CCS ready	■		■■			
Energy efficiency in buildings	■	■■	■■	■■■	■	■■■
Energy efficiency in transportation	■	■	■■	■■	■	■■
Efficient industry processes.	■■	■	■■	■	■	■
Medium term (5-15 years)						
Advanced power storage		■■			■	
Carbon scrubbing technologies (CCS and CCU)	■	■■■	■			
Advanced Nuclear reactors	■	■■■				
Next generation power electronics	■		■■		■	
Next generation biofuels	■■	■	■	■	■	
Hydrogen technology	■	■■				
Advanced geothermal	■	■■		■■		
Ocean energy	■	■■■				

■ Moderate impact
■■ strong impact
■■■ Very strong impact

5. Description of Short- and Medium-Term Technologies

Decarbonizing technologies to accelerate: short term (up to 5 years)

Lead author: Lin Boqiang, Dean, Institute for Studies in Energy Policy, Xiamen University, People's Republic of China

Supply side

1. Wind Power

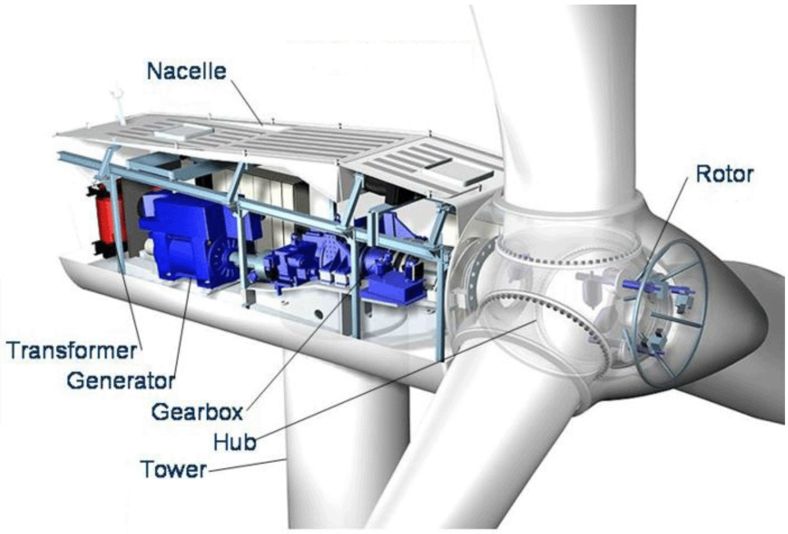
Reasons

Wind energy as an alternative to fossil fuels is plentiful, renewable, widely distributed and clean and it produces no carbon dioxide (CO_2) emissions during operation. The effects on the environment are generally less problematic than those from other power sources. Wind power is a robust technology that has made great strides in recent years. According to the recent development in the European Union and China of new constructions, onshore wind could also become an inexpensive source of electricity, competitive with or in certain places cheaper than coal, gas or fossil fuel plants. Significant technological advances are expected to continue for both onshore and offshore wind.

Sample technologies

Power from wind turbines is mainly determined by the wind regime at the site, turbine height and the efficiency of the turbine. Therefore, four trends are emerging significantly: (1) turbine nameplate capacity, hub height and rotor diameter in particular are increasing substantially; (2) more intelligent and lighter structures and advanced materials are being employed; (3) more efficient generators and converters are being developed; and (4) turbines originally designed for lower wind speeds are rapidly gaining market share.

Turbine for Wind Power Generation



Source: Roger Wendell (http://www.rogerwendell.com/wind.html)

Decarbonizing potential

Theoretically, wind supply could meet global energy needs while producing virtually no CO_2 emissions; therefore, wind power could contribute to decarbonization by reducing fuel combustion. According to International Energy Agency (IEA) scenarios, wind power could provide 1,500 terawatt-hours (TWh) per year of clean electricity in 2020 and thus could avoid the emission of about 1,100 $MtCO_2$ year.

Feasibility and scalability

Ongoing efforts in R&D for wind power technology are the main driver of this technology's development. Other factors to consider include achieving even higher penetration levels than today, suitability for site conditions, acoustic noise and visual appearance. Improved predictability (less than 5% deviation in wind forecast) and grid integration have dramatically enhanced wind power reliability.

Cost and affordability

Today wind is already competitive in many world regions without any additional support. The improvement of technology can be expected to reduce the levelized cost of wind power by 20-30% by 2030. In addition, the greater reliability and availability of wind power generation, as well as better grid connection, will make wind power increasingly affordable, given that access costs comprise a large share of total cost.

Accelerators and enablers

Wind power is a promising choice in the substitution of fossil fuel and its cost is quite competitive even at present. In several counties, wind power provides 15-30% of total electricity. The global call for CO_2 emission reduction requires governments to support the large-scale development of wind power by establishing effective carbon pricing for the energy sector (explicitly or implicitly), and supporting R&D.

2. Third generation nuclear energy

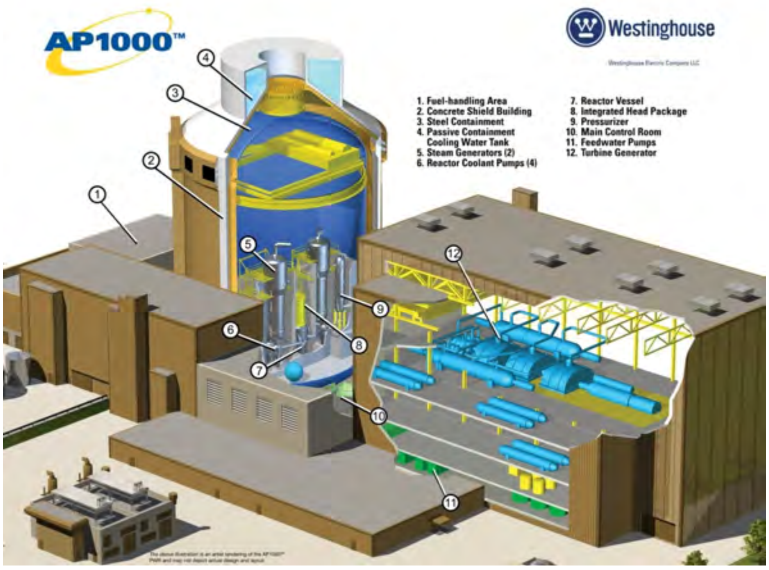
Reasons

Nuclear power generation has the capacity to provide large-scale CO_2-free electricity. With its cost competitiveness over wind and solar for baseload power production, nuclear power has a very significant role to play in decarbonization. The adoption of Generation III is promising due to its improved safety when compared with Generation II.

Sample technologies

Generation III technologies include the Westinghouse AP1000, the General Electric Economic Simplified Boiling Water Reactor, the AREVA EPR reactor, the General Electric Advanced Boiling Water Reactor, and the Mitsubishi Heavy Industries Advanced Pressurized Water Reactor, among others.

Descriptive Cutaway Rendering of the Westinghouse AP1000



Source: Westinghouse Electric Co.

Decarbonizing potential

Currently, more than 30% of all low-carbon electricity in the world is provided by nuclear energy. The number rises to more than 60% of all low-carbon electricity when hydroelectric power is excluded (Bloomberg New Energy Finance 2015). Therefore, nuclear power generation can provide large-scale CO_2-free electricity in countries where nuclear energy is socially and politically accepted as part of the energy mix.

Feasibility and scalability

Globally, nuclear power provides 11% of total electricity generation (Bloomberg, op. cit.). Nuclear power technology has already been proven. The main concern lies in public perceptions of safety, particularly after the Fukushima accident. Compared with Generation II, the third generation incorporates improved passive nuclear safety systems, such that safety has been significantly enhanced. The first Generation III reactor has been operating in Kashiwazaki, Japan, since 1996. Several others are under construction in Europe, the United States and China.

Cost and affordability

The main factors that affect the cost of nuclear power are the high capital cost of construction and decommissioning, and the costs of waste disposal. The fuel cost is relatively small. The learning-by-doing process in both manufacturing and construction signifies that the cost of nuclear power will decrease significantly with capacity expansion. In general, its cost could become competitive with coal and gas generation.

Accelerators and enablers

A continuing concern for the public and policy-makers is the safety of nuclear reactors, even though nuclear power provides promising availability of affordable low-carbon energy. After enforcing improved certification (especially for safety) and training programmes, governments should become the accelerators and enablers of nuclear energy.

3. Solar-PV

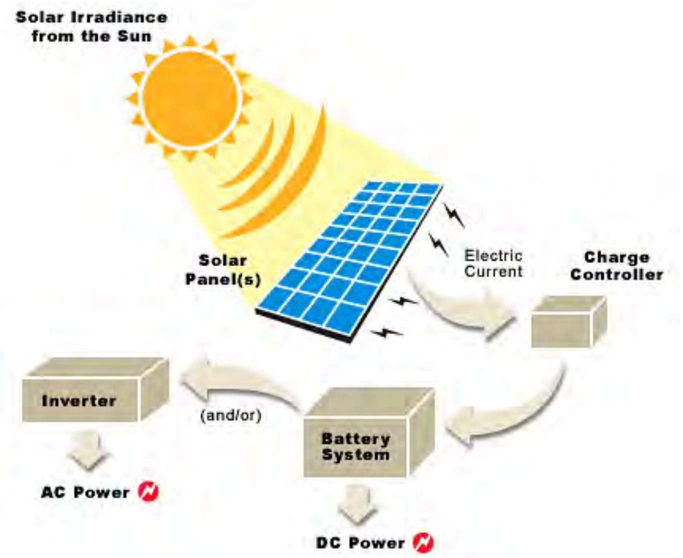
Reasons

Solar energy is the most abundant energy resource on earth. Solar-PV is a fast growing market, especially in certain industrialized countries, and it is expected to significantly expand in such emerging economies as China and India and in remote area where grid connections do not exist (i.e. Africa). Used as a decentralized and distributed solution, solar will have considerable impact in terms of deployment capacity and how emerging countries will consume electricity. Although the cost parity of photovoltaics (PV) compared with traditional energy types has not yet been fully achieved, it could be economically viable without subsidies in many countries and communities. The cost should continue to decrease substantially in the near future as the market expands and R&D efforts continue.

Sample technologies

Solar-PV systems can be grid-connected or off-grid. The latter could widely be used in water pumping or rural electrification. Solar-PV systems can be ground-mounted (e.g. in centralized electricity production facilities) or integrated into buildings.

Solar Power Systems



Source: Alternative Energy News

Decarbonizing potential

Solar power converts sunlight into electricity, either directly using PV or indirectly using concentrated solar power (CSP).Solar power generation does not emit CO_2 directly, except for the manufacturing and transportation of solar devices. The life cycle CO_2 emissions of solar power are from 22 to 46 grams per kilowatt-hour (g/kWh). These emissions are expected to decrease to 15 g/kWh in the future. By comparison, the averaged CO_2 emissions of combined cycle gas-fired power plants, oilfired power plants and coal-fired power plants are 499 g/kWh, 893 g/kWh and 955 g/kWh, respectively.

Feasibility and scalability

Worldwide, the average growth rate of solar-PV was about 40% per year between 2000 and 2013, and the cumulative installed capacity of PV reached 139 gigawatts at the end of 2013. More than 7% of electricity used in Italy is provided by solar-PV. The capacity of CSP increased tenfold in the same period, and worldwide cumulative CSP capacity at the end of 2013 reached 3,425 megawatts (MW). The rapid and large-scale deployment of solar power (either PV or CSP) proves its feasibility.

Cost and affordability

In most regions and countries, the cost of solar power is still high, causing an important barrier to solar power deployment. However, the expansion of capacity and intensive R&D efforts will reduce the cost of solar power quickly and substantially. To increase the large-scale deployment of solar power, further developments in distributional power systems, grids and storage are needed.

Accelerators and enablers

Currently, the costs of solar power in most regions are above grid parity. Solar power expansion must be encouraged to achieve economies of scale and is crucial of solar power is to reach grid parity worldwide in the near future. Thus government support through financial incentives and R&D, not only for the development of solar energy but also for storage technology, will play a key role. In addition, the adaptation of regulations and improvement of grid infrastructures are needed to accelerate deployment. Governments could consider connecting natural gas with solar power to develop distributional power systems.

4. Ultra-supercritical steam cycle coal ready for carbon capture and sequestration

Reasons

Overall, 40% of the world's electricity and about 80% of electricity in China (the world largest electricity generating system) is provided by coal. Coal plays an important role in electricity supply today and will continue realistically to do so in coming years, with many countries planning investments in new coal plants. Coal is a higher carbon fossil fuel compared to natural gas and oil and certainly to renewables. GHG emissions from coal plants represent a significant share of total emissions from the energy sector. With low-carbon development, ultimately coal plants will either have to be modernized with CCS or phased out entirely from the global energy system. Substituting coal with other lower-carbon fuels can be a solution in some cases. But, realistically, it will also be important to reduce emissions from existing and new coal-fired plants that will be built over the next 5 years. CO_2 emissions from coal-fired plants can be reduced by improving conversion efficiency through the modernization of existing plants and the deployment of high efficiency technologies in new plants and in those where the alternative is building plants with technologies that are less efficient. By making the plants CCS-ready – the retrofit of CCS technology when commercially available at affordable cost will be feasible.

Sample technologies

Technologies include nickel-based superalloys for larger components and higher temperatures, systems to manufacture (and weld) high-temperature alloy tubes and methods to test such materials more rapidly. Metallurgical and control problems still need to be resolved (IEA, *Energy Technology Perspectives: Scenarios and Strategies to 2050*, 2008).

1,000 MW Ultra-Supercritical Unit at the Shanghai Waigaoqiao Power Plant

Source: Cornerstone

Decarbonizing potential

Coal-fired power contributes to 40% of global electricity generation. The use of ultra-supercritical steam cycle (USCSC) technologies could raise the average efficiency of coal-fired power from the current level of 35% to around 45%. Thus, the decarbonizing potential of USCSC technologies is quite substantial compared to less efficient plants. The fear is that if many new fossil fuel power plants are built worldwide with no option for CO_2 abatement, large quantities of CO_2 emissions in the atmosphere will be “locked-in”, since such plants may well have an operational life of 40 years or more. Making the plants CCS-ready to retrofit when the technology is commercially available can enable much higher reductions in GHG emissions provided the plants are actually retrofitted.

Feasibility and scalability

Higher pressure and temperature increase the efficiency of the thermal cycle and power plants. In the quest for higher efficiency, the trend is to attain even higher operating pressures, which can be achieved by USCSC. Higher efficiency translates into reduced environmental impact. The requirements of energy resource conservation and environmental protection in the future may be one of the most important factors encouraging USCSC. Intensive R&D efforts, especially for thermo-stable materials, will further accelerate the large-scale adoption of USCSC. USCSC is a realistic and ready solution for countries that use coal in any case, particularly for developing countries in which energy savings are still critical for energy use. Effectively substituting USCSC for the current inefficient use of coal in these countries would lead to lower-carbon emissions. Therefore, USCSC combined with ensuring plants are CCS-ready could help in the transition to reduced emissions.

Cost and affordability

The cost of USCSC is comparable with that of subcritical steam cycle technology and is lower than other clean coal technology alternatives. Several pilot projects are under way to capture CO_2 from fossil-fuel-fired power plants but it is not yet fully commercially affordable to build power plants with CO_2 capture. The concept of a “capture-ready” power plant is therefore relevant. A capture-ready plant is a plant that can be retrofitted with CO_2 capture when the necessary regulatory or economic conditions are in place. As well as satisfying the essential requirements of space, access and a route to storage, further pre-investments can be made to significantly reduce the cost and downtime for the retrofit of CO_2 capture. Such pre-investments could be relatively attractive as they are generally low cost. Other potential pre-investments apply to specific capture technologies.

Accelerators and enablers

USCSC feasibility could be accelerated by basic research on new low-cost materials for high-temperature steam conditions. Governments funding this basic research will accelerate this technological innovation. Policy measures could be introduced to persuade developers to make their plants CO_2 capture-ready. They could include a legal requirement or incentives based on a definition of what is needed to qualify a plant as capture-ready. Even without such a requirement, plant developers may still choose to build capture-ready plants if they expect future regulatory requirements or a market price of CO_2 emissions that make the additional investment worthwhile, or to avoid the need to prematurely shut down plants (stranded assets).

Demand side

5. Energy efficiency in buildings

Reason

The building sector accounts for over one-third of total final energy consumption and is also an important source of CO_2 emissions. Achieving significant energy and emission reductions in the building sector is a challenging but achievable policy goal. Building efficiency is important in part because such a large portion of final energy is consumed in these structures, and in part because the costs of energy savings there tend to be among the lowest. Building energy consumption and related CO_2 emissions would further increase with the expansion of both residential/services building areas and the use of energy-consuming devices. Technologies in building energy efficiency can significantly reduce CO_2 emissions in new and existing buildings.

Sample technologies

Building-integrated photovoltaic (BIPV) electric power systems not only produce electricity, they are also part of the building. A wide variety of BIPV systems are available in today's markets. Most of them can be grouped into two main categories: facade systems and roofing systems. The related technologies include high-performance windows, vacuum-insulated panels and high-performance reversible heat pumps.

Building-Integrated Solar-PV System (left) and Building-Integrated Photovoltaic Electric Power System (right)

Source: Google Source: Wikipedia

Decarbonizing potential

These technologies help to reduce unwanted heat transfer. When combined with building-integrated solar-PV systems, some technologies can achieve 80% reductions in building energy consumption and CO_2 emissions. According to the IEA, through stringent efficiency standards, the promotion of heat pumps in lieu of electric resistance heating and greater electricity cogeneration with waste heat and renewables, electricity demand can be reduced by 2,000 TWh by 2050. This is equal to approximately half of current electricity consumption in the United States, or the entire electricity consumption of South America, Africa and the Middle East combined.

Feasibility and scalability

Normally, BIPV systems are less efficient than traditional rooftop PVs. But traditional PVs must be mounted on a rooftop as a separate, added-on construction step. BIPV systems enable the architecture, engineering and construction sectors to create buildings with higher energy efficiency, electric power self-generation and even aesthetics at the drawing-board stage. This actually cuts out an entire layer of engineering and construction issues. Regarding scalability, with nearly 85 million commercial buildings and single detached homes in the United States alone, according to the US Energy Information Administration, the market potential of solar window technology is drawing the attention of some fairly new photovoltaic start-ups. According to recent research and a report entitled “BIPV Technologies and Markets, 2015-2022” by NanoMarkets, the BIPV industry will grow from about $3 billion in 2015 to over $9 billion in 2019, and surge to $26 billion by 2022.

Cost and affordability

The cost of a BIPV system depends on the type of system and the PV technology used in manufacturing it. Currently, the construction costs are relatively high. To reach widespread application, cost reductions are essential. BIPV R&D should focus on achieving cost reductions by optimizing integration concepts and developing new building products and standardized products. In the long run, product standardization will be an essential element in reducing the cost of manufacturing BIPV systems.

Accelerators and enablers

In densely populated urban areas, limited roof surfaces of existing buildings may hinder the development of building-integrated solar-PV systems. For new buildings, BIPV systems would increase construction costs. For rural areas, both central and local government support is indispensable. Public-private partnerships should be considered to enable this.

6. Energy efficiency in transportation

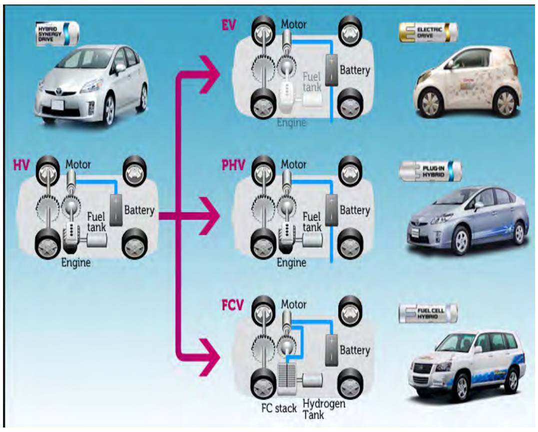
Reasons

Transportation accounts for more than half of the oil used worldwide and nearly 25% of energy-related CO_2 emissions. Critical technologies, such as vehicle on-board energy storage, are not yet technically mature. Thus, improving the fuel economy of transport by pursing energy efficiency is one of the most important and cost-effective measures possible.

Sample technologies
Some technologies can play important roles in achieving a low energy/CO_2 transport system. These technologies include advanced propulsion systems, green transportation systems (such as bus rapid transit, high speed rail and public bicycle systems). In the context of dynamical systems of traffic (propulsion systems) in the short term, hybrid technology and oil upgrading (clean fuel technology) are two main technologies.

Additionally, there are many aspects of energy efficiency in transport. For example, good traffic management is also important for fuel economy.

Plug-In Hybrid Electric Vehicles



Source: Google

Bus Rapid Transit

Decarbonizing potential
For electric vehicles (EVs) or plug-in hybrid electric vehicles (PHEVs), CO_2 reduction levels will depend on the proportion of miles driven using battery electricity from grid recharging in lieu of petroleum consumption in an internal combustion engine, and the electricity generation mix.

Feasibility and scalability
Many challenges, such as technology, cost and infrastructure, must still be addressed. Once feasibility is established, including high performing battery technology and reliable electricity recharging for EV/PHEV, scalability can follow.

Cost and affordability
The upfront cost of batteries is a challenge in the near future unless these costs to the consumer can be spread over several years. Green transportation (bus rapid transit, high speed rail and public bicycle systems, for example) has considerable economic and social benefits.

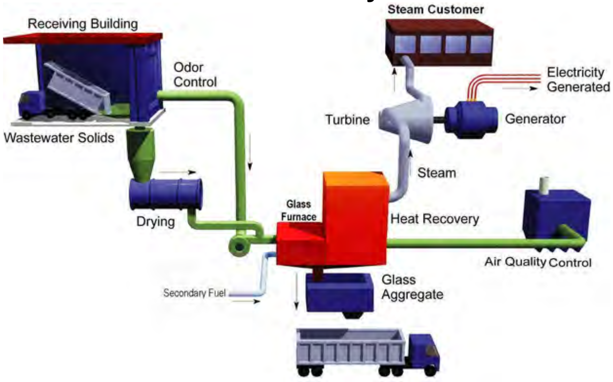
Accelerators and enablers
Consumer acceptance of EVs and PHEVs is a key factor determining the ultimate success or failure of these technologies. Reliable electricity supply must be available to recharger EVs/PHEVs. To promote green transportation, such as bus rapid transit and public bicycle systems, government and city administration support and planning are critical.

7. *Efficient industry processes*

Reasons
Industry accounts for one-third of global energy use and almost 40% of worldwide CO_2 emissions. Achieving substantial emission reductions in the future will require urgent action from industry. The application of the best available technologies worldwide would result in extensive energy savings and CO_2 mitigation.

Sample technologies
A number of cross-cutting options will be important if the industry is to reduce CO_2 emissions significantly, including greater biomass and waste use, fuel switching, CCS, motor and steam systems, combined heat and power (CHP) systems and increased recycling.

Combined Heat and Power System



Source: Google

F³ Factory
Source: F³ Factory (www.f3factory.com)

Note regarding the F³ Factory image above: A variety of chemical processes can be conveniently carried out in small mobile container factories (e.g. a chemical plant embedded in a 3m x 12m container) with a reduced energy consumption of up to 30% and a total environmental footprint reduction up to 50%. Used in this way, containers could drastically reduce logistical issues and ease seasonal production, providing benefits for local employment. Then, once the job is over, they would just go somewhere else.

Decarbonizing potential

The decarbonizing impact of these technologies is straightforward. However, their potential is affected by the use and optimization of energy-efficient industrial equipment and systems, and energy management.

Feasibility and scalability

Ongoing global R&D competition will be the most powerful driver of technological breakthroughs in carbon-free technologies. The rate of implementation of carbon-free technologies in practice depends on a number of factors, including capital stock turnover, relative energy costs, raw material availability, rates of return on investment, and regulation. Energy subsidies, for example, undermine the role of markets in driving greater energy efficiency. Governments should remove them.

For scale, funding at this early stage will probably be the biggest issue. Under the rigorous constraint of emissions abatement, scalability will be large. Some industrial processes, such as iron and steel, chemicals and petrochemicals, pulp and paper, aluminium and cement, all have large-scale potential from efficiency improvement.

Cost and affordability

The initial cost is relatively high because of capital stock turnover and equipment investment. However, the running cost tends to decline. The bigger the facility, the lower the operation costs.

Accelerators and enablers
The public outcry for a cleaner environment will be critical to enabling and accelerating the application of carbon-free technologies in industry processes. Rigorous environmental regulation and rational energy pricing systems should be considered to enable this.

Decarbonizing technologies to accelerate: medium term (5-15 years)
Lead author: Tatsuo Masuda, Visiting Professor, Nagoya University of Commerce and Business Graduate School, Japan

1. Advanced power storage

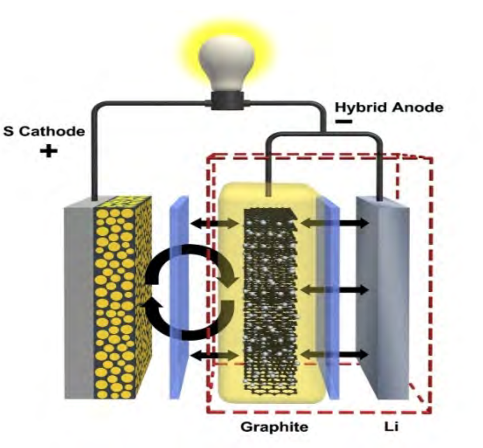
Reasons
Efficient and cost-effective power storage (e.g. batteries) is critical to mitigating the intermittent nature of variable renewable energy, promoting small- to medium-scale decentralized renewable solutions and drastically accelerating the use of EVs through extended mileage per charge. In addition, advanced power storage will contribute to the optimization of power supply and demand, ranging from residential levels to wider grid levels.

Sample technologies
Many technologies are under development, particularly on advanced batteries using various materials for electrodes, electrolyte and catalyst. Among these, two specific technologies are highlighted.

(1) The first is lithium-sulphur batteries using sulphur as the cathode. The use of cheap and abundant sulphur as the cathode is a cost advantage for this technology, in addition to higher energy density than currently prevailing lithium-ion batteries. Despite remaining technical challenges, commercialization will occur much sooner than lithium-air batteries (see the first illustration below).

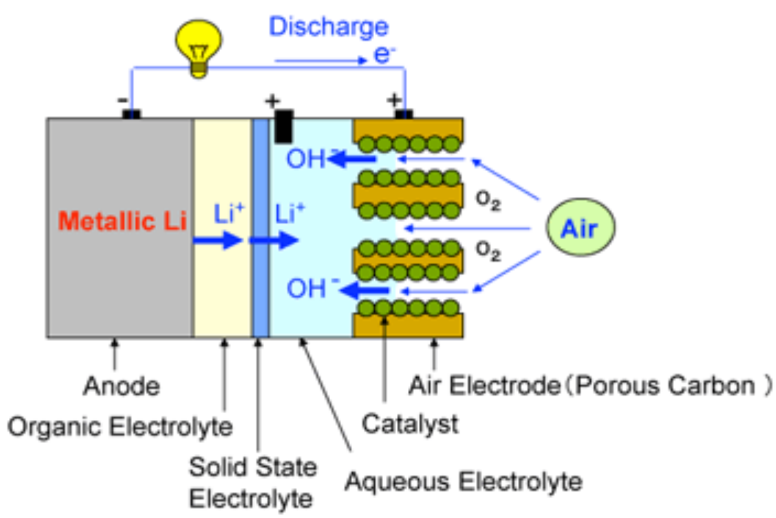
(2) The second is lithium-air batteries using oxygen from the air as positive electrode active material. The advantage of this technology is the decreased weight, with high energy density allowing extended mileage per charge for vehicle application (see the second illustration below).

Lithium-Sulphur Battery



Source: United States Department of Energy

Lithium-Air Battery



Source: National Institute of Advanced Industrial Science and Technology (AIST)

Decarbonizing potential
To make the best use of variable renewables, the role of power storage is critical. For example, electricity generated from solar and wind could be used as "quasi" base load power if storable at reasonable costs. This will further accelerate the introduction of renewables, thus contributing to decarbonization. Vehicle application of advanced batteries will further extend the cruising range of EVs, leading to wider use. The Well-to-Wheels energy efficiency is far higher for EVs (around 35%) than for internal combustion engines (around 13% for gasoline).

The composition of the energy mix for the production of electricity used for electric vehicle recharging will influence the decarbonization potential.

Feasibility and scalability

The chemical reaction inherent to batteries is thought to be in a “black box”, hindering the progress of innovation despite massive efforts by both the private and public sectors worldwide. This is particularly the case for lighter and smaller batteries for vehicle applications. Ongoing global R&D competition will be the most powerful driver of technological breakthroughs in this area.

Cost and affordability

The use of more cost-effective materials and mass production will make power storage increasingly affordable, as attested by many electric/electronic devices in the past.

Accelerators and enablers

Although this is one of the most promising areas of business opportunity, progress is somewhat slower than expected. Accelerating global competition by mobilizing the influence of institutional investors worldwide in this direction is needed (see the Portfolio Decarbonization Coalition’s efforts). Focused research funding by governments is also critical.

2. *Carbon scrubbing technologies (CCS, CCU)*

Reasons

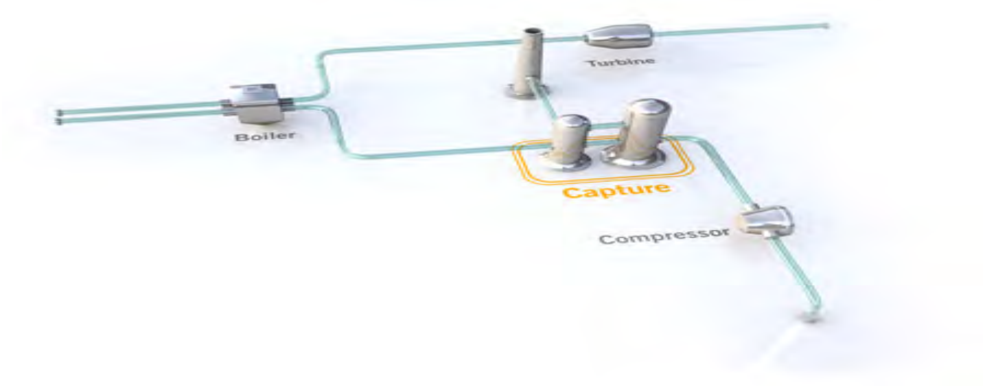
Considering the reality that fossil fuels will remain a major source of energy for at least a few more decades, and that many industrial processes currently do not have a renewable or nuclear-based alternative, the development of Carbon Capture and Sequestration (CCS) is of utmost importance. CCS has long been discussed and experimented. However, its drawbacks are high costs and the perception of treating CO_2 as waste to be stored in geologic reservoirs. The components – carbon capture, CO2 pipelines, and CO2 geologic injection – have long been used in industry for decades. But only recently have they been integrated and applied as an CO_2 emissions abatement tool for power plants and other industrial sources. Because this application is new, it has the high cost that all new technologies see at the beginning of their maturation process. As with wind and solar technologies, deployment can drive costs down.

Despite its importance and even if the costs were to decrease, CCS will also be confronted with the possibility of leakage, long-term liability issues and NIMBY (“Not In My Back Yard”) sentiment. Therefore, carbon capture and utilization (CCU) using CO_2 as feedstock for valuable products should be pursued in parallel with CCS and can improve the business case by attributing a market value to CO_2. This includes but is not limited to the use of CO_2 for enhanced oil recovery (EOR). At the same time, to maximize the potential of decarbonization in the fossil-based power sector, CCS and CCU should be combined with high-efficiency coal-fired power plants (e.g. ultra-supercritical steam cycle) or gas-fired power plants (e.g. combined cycle gas turbine plus solid oxide fuel cell). The technology should also be optimized for use in existing power plants. Further investment is needed for CCS and CCU technology innovation for both new and existing units as well as industrial sources.

Sample technologies

The basic technology needed for CCS has already been applied as part of enhanced oil recovery, injecting CO_2 mostly from natural sources into oil reservoirs, where the costs of CCS have been paid off by the additional production of oil. To apply CCS widely to the major sources of CO_2 emissions from artificial sources such as coal-fired power plants and cement plants, the cost-effective technology, particularly for capturing CO_2, should be further developed (see the illustration below).

Post-Combustion Capture



Source: Global CCS Institute

While CCS is a high-tech and still costly option, soil carbon sequestration (soil CCS) could offer a low-tech and inexpensive option, which it would be worthwhile to test and prove in parallel with CCS. CCU requires technology either to fix CO_2 into inert carbonates (e.g. through mineral carbonation) or to use CO_2 to produce valuable products.

Decarbonizing potential
The decarbonizing impact of these technologies is straightforward. Moreover, it should be noted that CCS is the only technology that can potentially decarbonize the 1.8 terawatts of existing coal units, and the hundreds of gigawatts of additional fossil units in the construction pipeline, many of which will likely remain operating for decades.

Feasibility and scalability
CCS is technically feasible, and already nearly 80 large-scale projects are at various stages of development, according to the Global CCS Institute. Among these, the first commercial-scale application to a coal-fired power plant, the Boundary Dam CCS Power Plant, was launched in October 2014 in Saskatchewan, Canada (CO_2 capture capacity of 1 Million tonnes per annum; see the photo below). This project is favoured with a nearby source of coal, the partial sale of captured CO_2 to enhanced oil recovery, and government subsidies. Nevertheless, it provides extremely encouraging proof of feasibility. Two other large coal CCS projects are under construction in Mississippi and Texas, USA. Also, trials are in progress to use captured CO_2 as raw materials for the culture of microalgae suitable for biofuel or chemical feedstock.

Boundary Dam CCS Power Plant

Source: SASKPOWER CCS

Cost and affordability
The road will be long for CCS to be widely commercialized, due to its current initial high costs and potential social acceptance issues. As has been the case with renewable energy technologies or other power plant pollution controls, the path to affordability will likely require government support or the utilization of captured CO_2 to produce valuable products or global carbon pricing at a substantial level.

Accelerators and enablers
Given the absence of global carbon pricing, regulatory and financial frameworks favourable to CCS will be critical. At the same time, both central and local government support to facilitate public understanding and confidence building will be indispensable to overcome NIMBY sentiment. The commercial use of captured CO_2 would change the situation substantially. As the development of CCU is far behind CCS, a radical enabler will be needed, such as a multibillion-dollar fund devoted to CCU research and development as a public-private partnership.

3. Advanced nuclear reactors

Reasons
Despite controversy over nuclear power, the imperative need for decarbonization requires this carbon-free option for baseload power generation to be in the global energy mix. However, despite the decreasing costs of reactor units being built in Asia, the costs of building large-scale nuclear power plants still remain high relative to unabated fossil generation (coal in Asia, natural gas in the United States) because of complex safety requirements, a long lead time due to the inherent

problems of large-scale construction, specific project management failures, and the failure to address political and social concerns. Therefore, it is necessary to introduce advanced nuclear reactors that are inherently safer, cost competitive and designed for mass production with an improved waste profile. The need for accelerated electrification in developing countries could partly be filled by the deployment of such reactors as distributed power sources to cover the regions out of reach of the major power transmission networks.

Sample technologies

Four specific technologies are highlighted:

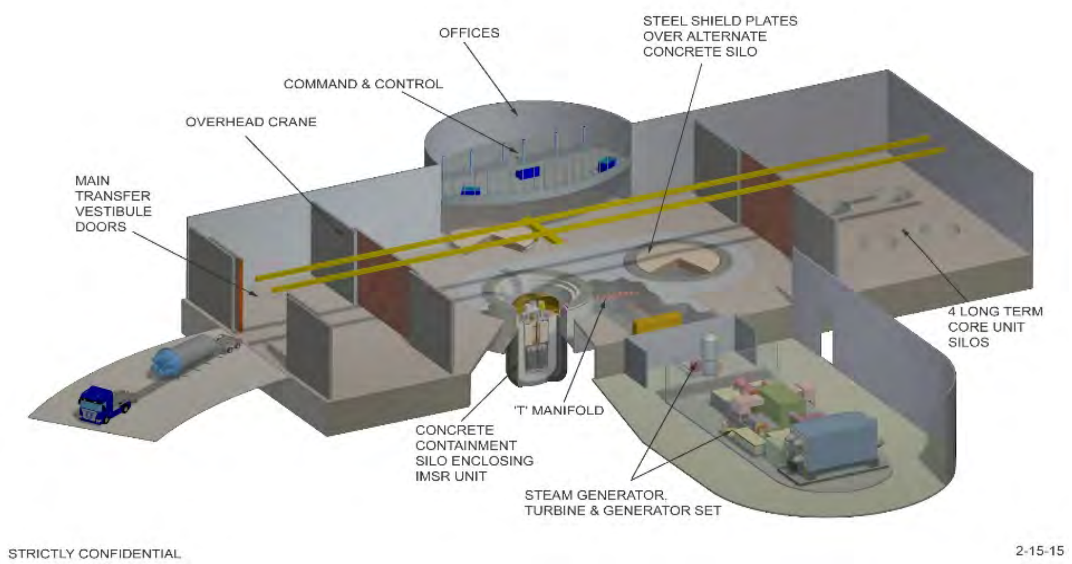
(1) The first is the Integral Molten Salt Reactor, which could be commercially deployable before 2030. This technology could generate electricity at relatively low cost with a low-waste profile by recycling the plutonium it produces (see the first illustration below).

(2) The second example is a micro nuclear generator called "U-Battery", basically based on existing technology but configured for modular deployment. Two units of 5-10 MW each could be accommodated in the space of a tennis court. The system is designed to operate for 50 years, with minimum maintenance every 5 years at the same time as the refuelling cycle (see the second illustration below).

(3) The third example is TerraPower's liquid sodium-cooled fast reactor, the traveling wave reactor (TWR), which features innovations in metallic fuel, cladding materials and engineering that allows it to utilize depleted uranium as its primary fuel. The TWR's design greatly simplifies the nuclear fuel cycle by reducing and eventually eliminating the need for enrichment, eliminating reprocessing, and greatly reducing waste storage and disposal. TerraPower aims to achieve the start-up of a 600-megawatt electrical (MWe) prototype in the mid-2020s, followed by global deployment of 1,150-MWe commercial plants (see the third illustration below).

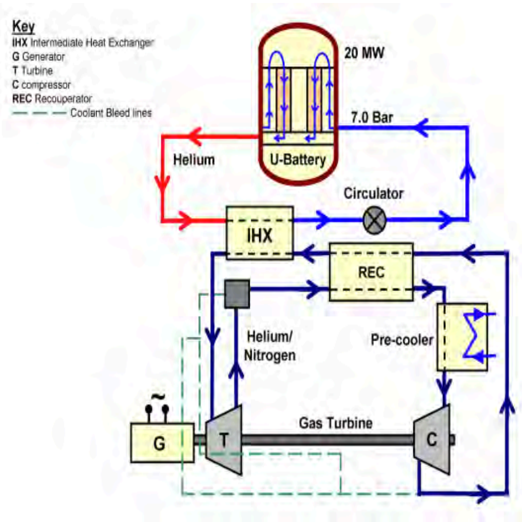
(4) The final example of an advanced nuclear reactor design is being developed by UPower, which is building a 2 MW reactor based on demonstrated reactor technology. The reactor ships in a shipping container and is designed to behave like a nuclear battery that is deployed for 12 years between refuelling. The reactor has no moving parts in the reactor block, is cooled solely by natural forces and can consume nuclear waste and convert it to energy. The technology is designed to offer a low-cost, highly modular and scalable approach to nuclear power that can be deployed globally with anti-proliferation capabilities.

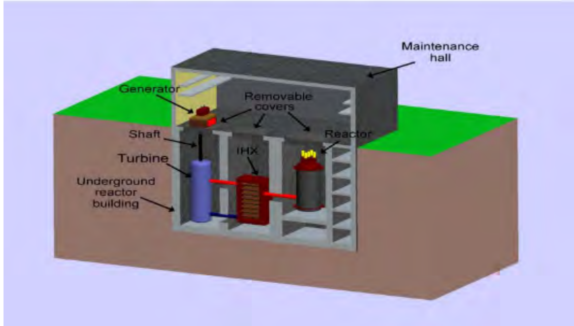
Integral Molten Salt Reactor Concept



Source: Terrestrial Energy Inc.

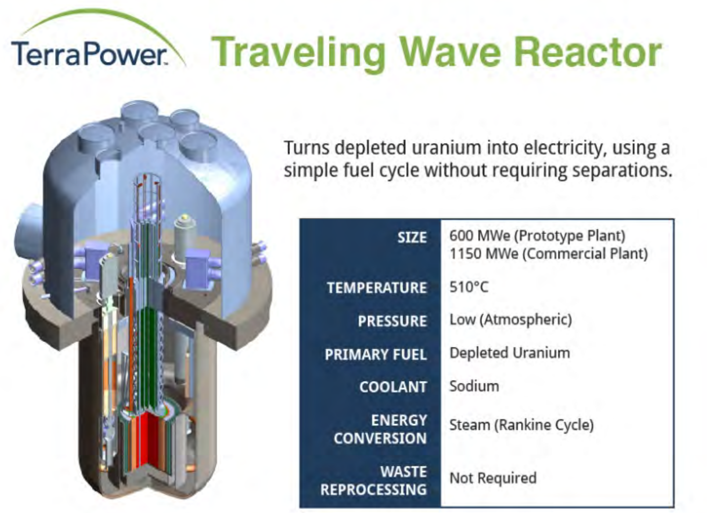
U-Battery Concept





Source: Atomic Acquisitions

Traveling Wave Reactor Concept



Source: TerraPower

Decarbonizing potential

Due to the carbon-free nature of nuclear power, its decarbonizing effect is undisputable.

Feasibility and scalability

Its feasibility should be proved by the successful construction and operation of prototype reactors. For this purpose, funding at this early stage will probably be the biggest issue, as will the availability of pilot facility sites.

Cost and affordability

The widespread diffusion of small modular reactors will reduce the equipment costs as well as construction time and costs. If prototype reactors function well enough to convince successive commercial deployment, factory-fabrication will make good headway towards affordability.

Accelerators and enablers

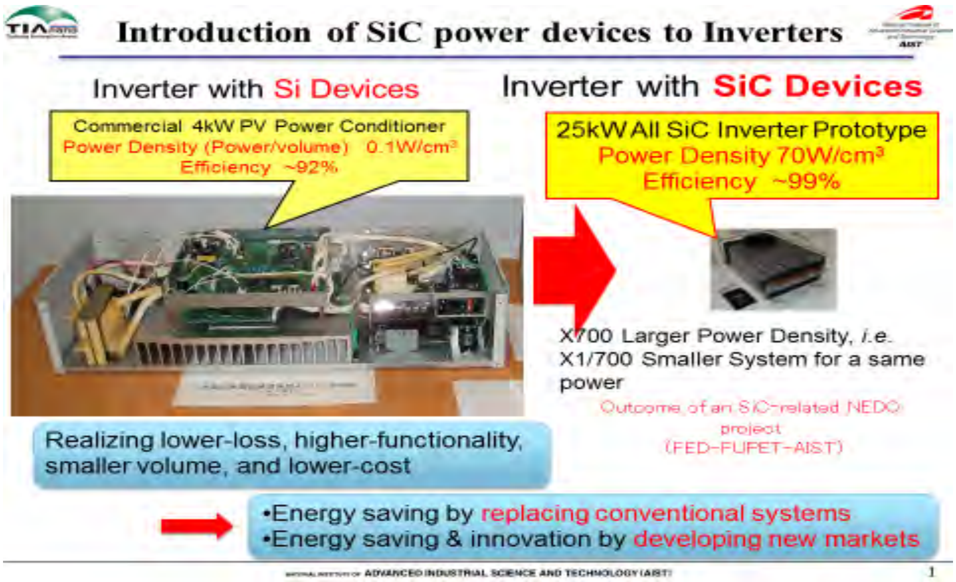
As the current regulatory regime pertains to large-scale plants, a clear and predictable regulatory pathway adjusted for small reactors should be developed. Financial incentives and assistance, particularly at the pilot phase, will help shorten the time needed for commercial deployment. Government support, both central and local, in facilitating public understanding and confidence will be indispensable to overcome NIMBY sentiment.

4. Next-generation power electronics

Reasons
Power electronics is technology to flexibly control and convert electric power (voltage, current and frequency) by using semiconductors as critical components. In the age of electrification, this technology is applied everywhere in the form of DC-DC converters, DC-AC inverters and others. As the conversion process itself consumes substantial electricity, improving conversion efficiency will contribute massively to power savings.

Sample technologies
It's a proven fact that gallium nitride (GaN), known for blue LED, and silicon carbide (SiC) dramatically improve power conversion efficiency, among other attributes. Both materials enable the miniaturization of devices. For example, an electronic router using GaN will consume only one-sixth of the electricity of a conventional one. The size of an advanced inverter using SiC could become just 1/700th of the conventional power inverter (see the illustration below).

Introduction of SiC Power Devices to Inverters



Source: National Institute of Advanced Industrial Science and Technology (AIST)

Decarbonizing potential
Estimates suggest that global electricity consumption by electronic routers alone in 2023 will become as large as the total electricity consumption of Japan today if conventional technology continues to be applied. Therefore, the application of new technology could make a big difference, and could similarly be applied in the areas of other devices.

Feasibility and scalability
Electrification will proceed at an accelerated pace all over the world, so making the best use of electricity will become a very hot issue among manufacturers of electricity-related equipment, such as converters, inverters and routers. Competition between the players will naturally accelerate innovation and help make successive breakthroughs.

Cost and affordability
Competition and mass production, combined with the introduction of more cost-effective materials, will make such equipment affordable, as has been the case in the past with regard to many other electric and electronic devices.

Accelerators and enablers
The positive effects of competition among the market players (e.g. companies and laboratories) will accelerate the pace of technological innovation and the dissemination of devices.

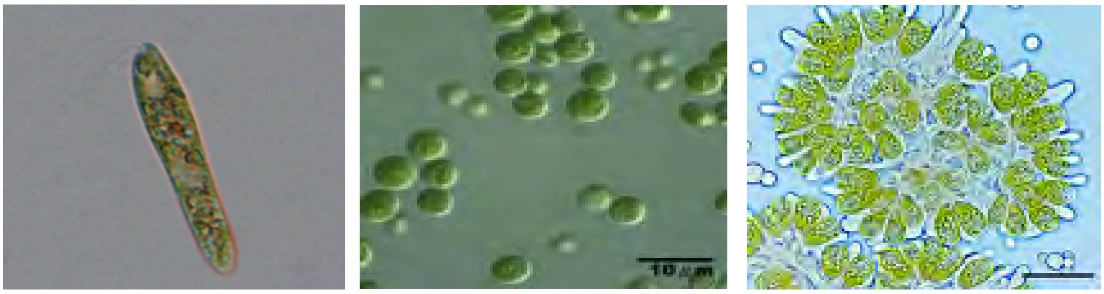
5. Next-generation biofuels

Reasons
Considering the continued need for liquid fuels for transport in the foreseeable future, carbon-neutral biofuels should be increased to decarbonize this sector as much as possible. Certain prevailing biofuels have limitations due to their competition with food and animal feedstock (e.g. corn), so developing sustainable ways of producing biofuels from non-food plants is critical. Various institutions have been conducting research on the production of biofuels from lignocellulose (e.g. wood) for over a decade. More recently, algae have drawn wide attention among biomass materials as feedstock to produce liquid fuels. However, the technological challenges to make them competitive with conventional fuels are significant.

Sample technologies
Among almost countless groups of algae, some species of microalgae are known to have rich fuel components (see the photos below). But technological challenges exist throughout the cultivation, concentration, separation, extraction and purification processes.

Microalgae Suitable for Fuel Production

Euglena Chlorella Botryococcus



Source: Kobelco Eco-Solutions Co.

Decarbonizing potential
Biofuels are carbon-neutral, except for the CO_2 emissions resulting from the production and delivery processes. In the case of microalgae, the carbon footprint differs according to the cultivation method employed:
(1) Photosynthetic cultivation using CO_2 and sunlight
(2) Heterotrophic cultivation using O_2 and organic matter such as glucose
The former has larger potential in terms of decarbonization, but productivity is low. The latter uses energy even in the process of cultivation, but productivity is high.

Feasibility and scalability
The major steps to make fuels from microalgae commercially feasible are:
(1) Screening microalgae for rapid and high-density cultivation
(2) Establishing a cost-effective method for high-density cultivation
(3) Establishing a cost-effective method for harvesting and concentration
(4) Establishing a cost-effective method of extraction and refining.
Scalability will follow once the above process has been established.

Cost and affordability
Some types of microalgae are suitable as raw materials for medicines, cosmetics and food supplements, such that the relatively high costs of microalgae cultivation and processing could be absorbed. However, competing with fuels will be difficult and may require another decade or so before the costs are low enough to compare with traditional liquid fuels.

Accelerators and enablers
Biofuels accounted for about 2% of global energy demand in the transport sector in 2012 (IEA *World Energy Outlook 2014*), but their share will increase as next-generation biofuels flow into the market. With the comparative advantage of producing biofuels across regions, cross-border trade should be accelerated for wider utilization. Introducing common international standards and specifications related to biofuels would facilitate such trade. It is thus very encouraging that international initiatives to

make these standards and specifications compatible across regions are taking place (e.g. in the European Union, the United States and Brazil).

6. Hydrogen technology

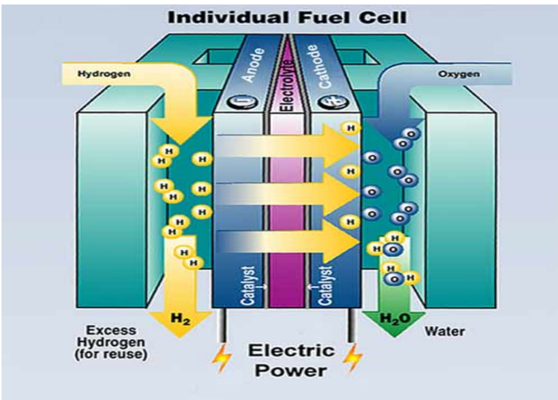
Reasons

Hydrogen has been widely used for industrial purposes, but not as a fuel until recently. Although carbon-free, due to its low energy density, hydrogen has less value as a fuel unless used in fuel cells, to generate electricity through a chemical reaction between hydrogen and oxygen (from the air) with higher power generation efficiency. More importantly, the by-product of this chemical reaction is only water (H_2O), which is environmentally friendly. In some developed countries, stationary fuel cells are installed for residential use and, very recently, even fuel cell vehicles (FCVs) have started to be sold commercially, albeit supported by subsidies. Although the use of hydrogen technology is in its infancy, it will become an important option for decarbonizing the energy system. For the time being, hydrogen comes from fossil fuels or as a by-product of industrial processes.

Sample technologies

Since the late-2000s, fuel cell cogeneration systems for power generation have become commercially available for residential use in some developed countries. In the case of Japan, hydrogen extracted from city gas is used, achieving some 80-90% thermal efficiency. Also, larger fuel cells of over 1 MW became marketable for industrial use as distributed power sources. These are stationary fuel cells, which are less technologically constrained in size and weight as compared to those for vehicles. The world's first commercial FCVs were sold by Toyota in early 2015. They are still extremely expensive, and related infrastructure, such as hydrogen stations, are yet to be constructed to any extent (see the illustration and photo below).

Fuel Cell Mechanism



Source: HyGen Industries

MIRAI-World's First Commercial FCV

Source: Toyota

Decarbonizing potential

Hydrogen technology will make a substantial contribution to decarbonization only when its major fuel, hydrogen, is supplied from decarbonized energy sources, such as solar, wind or nuclear. Its dissemination will largely be affected by the speed of the infrastructure development that is tailor-made for the "hydrogen society", which is different from that needed for the current "hydrocarbon society".

Feasibility and scalability

The beginning of the hydrogen society brings many challenges that must be addressed, related to the technology, its costs and infrastructure (e.g. storage and distribution) as well as the regulatory frameworks. Judging from the successful installation of stationary fuel cells at this early stage, hydrogen technology could well be increasingly used if the challenges are addressed step by step.

Cost and affordability

Hydrogen technology will not contribute seriously to decarbonization unless hydrogen taken from carbon-free sources (including renewables) becomes readily available at competitive prices.

Accelerators and enablers

While the development of fuel cell cars has proved challenging, it is notable that Toyota made some 5,680 hydrogen-power patents available royalty-free in January 2015. This initiative will help to speed up global competition, the most powerful accelerator of FCV development, which should be underpinned by public-sector assistance to develop the necessary infrastructure to accommodate FCVs.

7. Advanced geothermal

Reasons

Geothermal energy is one of the most untapped resources despite its inherent abundance and attraction as a baseload power source (1.5% of global power generation from renewables in 2011: *IEA World Energy Outlook 2013*).Due to its relatively long history of deployment – since around the oil shocks of the 1970s – some of its technology is relatively mature and commercially competitive. It is located where heat is relatively easy to harvest, as in such countries as Iceland and the Philippines. Given its carbon-free nature, the use of this resource on a large scale as well as in a variety of locations should be more rigorously pursued.

Sample technologies

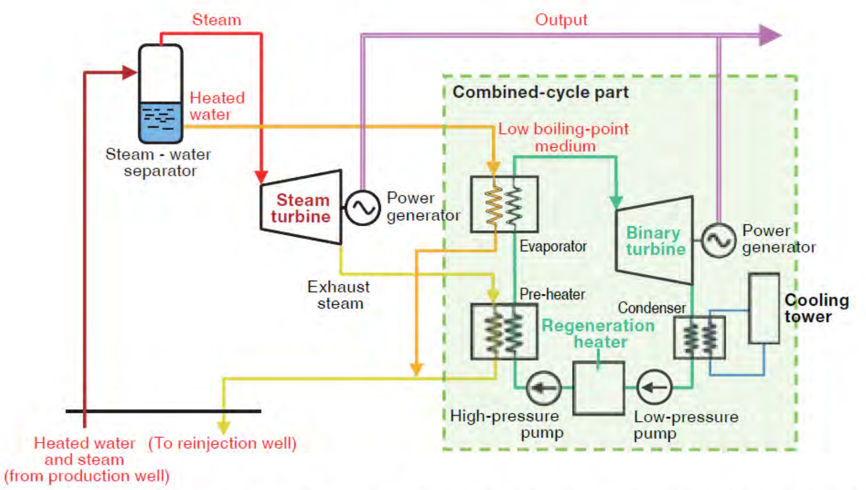
Geothermal power generation involves three major technologies, two of which (the flash system and binary cycle system) have almost reached maturity. Research to combine these two systems is taking place (see the first illustration below).

(1) The flash system takes steam from hot geothermal reservoirs (200-350℃) to spin the turbine for power generation while pumping the liquid back into the reservoirs.

(2) The binary cycle system allows cooler geothermal reservoirs (80-150℃) to generate power by using heat exchangers.

(3) The enhanced geothermal system (or hot dry rock geothermal power) uses hot dry rocks at a depth of around 5 kilometres as a heat source by pumping high pressure cold water at that depth. The heated water is used for power generation. As hot dry rock structures are found in various locations, this technology will broaden the availability of geothermal power (see the second illustration below).

Combination of the Flash System and Binary Cycle System

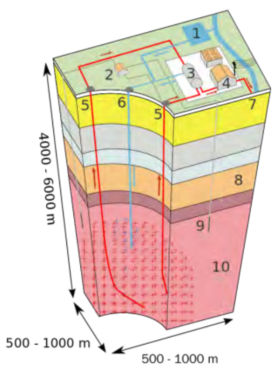


Combined-cycle power generation system (image)

Source: New Energy and Industrial Technology Development Organization (NEDO)

Enhanced Geothermal System

1. Reservoir
2. Pump house
3. Heat exchanger
4. Turbine hall
5. Production well
6. Injection well
7. Hot water to district heating
8. Porous sediments
9. Observation well
10. Crystalline bedrock



Source: Wikipedia

Decarbonizing potential
Among the various renewable energy sources, the advantage of geothermal power is its regularity unlike wind and solar. Due to its abundance, if properly used its potential to contribute to decarbonization is high.

Feasibility and scalability
The enhanced geothermal system may require more time and trials to establish it as a reliable technology. Some reports suggest the system may have triggered earthquakes in some regions due, probably, to the use of hydrofracturing technology.

Cost and affordability
The cost of geothermal power is one of the lowest among renewables, particularly for single flash systems installed in favourable locations. The initial cost is relatively high, including the lead time for the commissioning, while the running costs tend to be low.

Accelerators and enablers
Public acceptance will be critical to enable and accelerate large-scale geothermal power generation. Therefore any environmental concerns, such as the possibility of earthquakes associated with the enhanced geothermal system, should be fully addressed through R&D, with assistance from central or regional governments as necessary.

8. Ocean energy

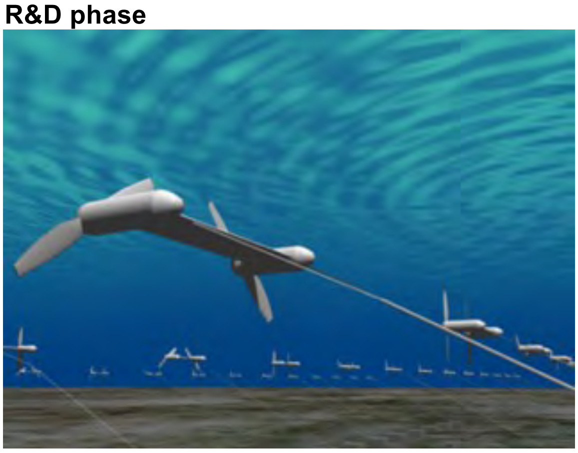
Reasons
The history of technological developments in the use of ocean energy for power generation extends over a century, with various technologies having been tested and employed. However, the road is long before humanity can fully benefit from its potential, due to huge technological and engineering challenges. The merits of ocean power (tidal power and marine current power) include predictability and a large resource base. This energy warrants greater attention as it relates to decarbonization.

Sample technologies
Technology in the use of tidal power is more advanced than that for marine current or marine temperature power. The Rance Tidal Power Station in France is the world's first tidal power plant; several others range from 20 to 254 MW (see the photo below). Marine current is very attractive for power generation due to the strong and constant flow in one direction. However, it is usually located several kilometres off the coast where the seabed tends to be deep, which poses multiple technological and engineering challenges (see the illustration below).

The Rance Tidal Power Station - 240 MW, Established in 1996

Source: Wikipedia

Underwater Floating Ocean Current Turbine - R&D phase



Source: IHI Corporation

Decarbonizing potential
Although extremely underused, ocean energy has huge potential for decarbonizing the energy system due to its abundance.

Feasibility and scalability

The success of certain types of ocean energy power generation offers accumulated know-how that could be used along with the expertise of shipbuilding and underwater engineering businesses. Scalability will follow when feasibility and optimum design and maintenance methods are established.

Cost and affordability

Unlike photovoltaic power generation, the bigger the facility, the lower the cost is per KWh in ocean energy power generation. However, maintenance costs could remain high due to the nature of the underwater structure.

Accelerators and enablers

Ocean energy power generation could be a viable option, particularly for islands that are out of reach of the power transmission networks. But due consideration should be given to this technology's impact on marine ecosystems and fishery. Public-private partnerships could be considered to enable research in this area.

6. Conclusion and next steps

This working paper has highlighted the importance of accelerating innovation and deployment of technologies that have high potential to decarbonize energy, and touched on some of the approaches to enabling that acceleration. In coming months the Global Agenda Council on Decarbonizing Energy will focus on a selection of these solutions with the goal of accelerating developments, in collaboration with interested and relevant actors.

7. Endnotes

[1] BP Statistical Review of World Energy 2015, see http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy.html.
[2] Ibid.
[3] *The Future of Electricity: Attracting investment to build tomorrow's electricity sector*, World Economic Forum 2015, Geneva.

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