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Energy, society and science: The fifty-year scenario

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ABSTRACT

A vibrant, interactive, and rapidly advancing global society needs an adequate, low cost, predictable and diverse supply of energy; a stable climate; and an international market for energy that mediates across countries, regions, and energy carriers. The science discoveries needed to achieve these energy and societal outcomes are analyzed.

1. Introduction

The next fifty years will witness historic transitions in energy and society. Sustainable energy technologies such as wind, solar, biofuels, carbon sequestration, and electric vehicles are growing in our energy profile [1]. The old paradigm of a few technologically and economically advanced countries dominating the global stage is giving way to the growing aspirations and greater participation of developing countries in world affairs, driven by their desire to secure the societal benefits of economic growth and advanced technology. Increased globalization driven by widespread education, communication, trade, and exchange of people and ideas provides the means for developing countries to achieve their economic and technological aspirations. It is increasingly recognized that a high standard of living is a dynamic benefit: continuous and significant advances in science, technology, innovation, and competitiveness are critical to achieving and maintaining a high quality of life.

2. Energy and society in fifty years

Energy is a basic human need, like food, shelter and mobility, pervading all aspects of our personal, professional, civic and international lives. Access to energy enables or limits human aspirations, as reflected in the correlation of energy consumption with the human development index [2]. The societal benefits of technology, including modern energy-efficient residential and commercial buildings, farm-raised crops and animals, medical diagnosis and care, transportation by car, truck and air, communication of knowledge, information and ideas by electronic media and the rapid exchange of goods and

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services; all represent energy embodied in the materials and systems of society's infrastructure and expended in its operations.

To thrive and advance in the era of globalization, society must meet three basic energy challenges: adequate supply, stable climate and a transparent international energy market. These three challenges are outlined below.

2.1. First priority: adequate, low cost predictable energy supply

A scarcity of energy due to short supply or high cost limits the aspirations of society by restricting the technology that can be deployed and operated, the commercial trade that can be carried out and the cultural advances that can be achieved. Society responds not only to the quantity and cost of energy, but also to the reliability and predictability of its supply. With the notable exceptions of the decade starting in 1974 and recent history since 2003, oil prices have been relatively stable since 1880 [3,4]. This stability and predictability enhances energy security by promoting strategic long term planning by households, governments, businesses and societal institutions, encouraging them to implement the most strategically efficient and effective energy sources and operational technologies as they become available. The cost-benefit analysis of a given innovation or strategic trajectory can be evaluated over the long term with confidence and used to guide decision-making. In contrast, the recent price for oil has been volatile, with sharp increases and decreases driven by geopolitical events, financial crises and economic uncertainty. Volatility encourages short term tactical planning and reluctance to commit to innovative new technologies, business plans and strategic trajectories whose long-term economic viability cannot be established.

2.2. Second priority: climate stability

Climate stability [5] is a requirement for a vibrant, interactive and rapidly advancing global society. The evidence that climate change is occurring is overwhelming, reflected in increasing surface temperatures, rising sea levels, decreasing Arctic snow and ice cover, migration of species, shifts in plant hardiness zones and many other indicators [6–8]. Disruption of stable climate threatens many of the underlying foundations of global society, including agriculture and food production, commerce, coastal access to oceans, energy production, human health and ecosystem stability. The human and economic cost of climate disruption is high. The discretionary resources in developed and developing countries that remain after basic needs of food, shelter and health have been met are limited. These discretionary resources are the reserve that enables the forward progress of society through discovery of new phenomena, the development of new knowledge, implementation of innovative technology and adoption of new societal and cultural institutions that deliver greater service, higher standards of living and increased quality of life. These same reserves must cover the cost of unplanned natural events such as climate change. The high human and economic cost of climate disruption impedes or stalls technological and social progress of developed and developing countries toward higher levels of health, education, income, economic growth and environmental quality.

2.3. Third priority: international energy market

A vibrant, interactive and rapidly advancing global society requires an international market in energy that mediates across countries, regions and carriers of energy. Such a market enables countries to make informed energy and climate decisions that reflect their individual needs for energy and economic growth consistent with their national aspirations. An international market in energy would embody the economic principles of supply and demand, equality of access, and orderly processing of transactions by a transparent procedure. Such markets have proven their value in directing limited resources to the most effective uses, in providing a level playing field for competing players and in raising the long-term fortunes of all players. An international market in energy, like all markets, would inevitably be subject to mutually agreed restrictions, for example, to curb manipulation or reduce volatility. An international energy market provides choices among interchangeable energy carriers, eliminates exclusive two party contracts based on the geopolitical dominance of one the players, and promotes predictability based on transparent transaction procedures. In such a market players can better predict the outcomes of their own strategic plans and the impact of changing global energy conditions.

The international oil market is a good example of an international market for energy [9]. It mediates across the 31 varieties of crude oil, setting a price for each based on quality that allows substitution of one variety for another in an orderly and obvious way. The oil market responds to global shifts in supply and demand, and not to the whims of individual buyers or sellers unless they control a large enough market share to shift the global balance. In the best fifty-year global scenario, similar international markets would mediate not only oil but all forms of energy including gas [10], coal, biofuels, solar chemical fuels, uranium, hydrogen and electricity. Furthermore, these energy carriers would be fungible, so that a shortage in oil supplies could be compensated, for example, by increased use of gas or nuclear electricity. Establishing such a market requires not only social, economic and political institutions, but also science and technology breakthroughs to allow technical interchangeability among the energy carriers such as chemical fuels, electricity, heat and light. Interchangeability among these carriers now exists, as in combustion of chemical fuel to rotate a turbine driving a generator that produces electricity or in electricity heating a filament that emits incandescent light. Science breakthroughs are required to raise the efficiency of the interchanges among energy carriers, and to create new conversion routes, that, for example, eliminate heat as an intermediate carrier. Electrochemistry converts the energy in chemical bonds directly to electricity without combustion, and light emitting diodes convert the energy of electricity directly to light without heat.

The preferred global society we imagine in fifty years embraces rapid growth of developing economies, steady growth of developed economies, aggressive pursuit of discovery science, development and deployment of innovative technologies based on future discoveries, lively communication, trade and exchange of people and ideas across national and regional boundaries, and globalization of opportunity and participation in scientific, technological, economic, social and cultural advances. Achieving this vibrant global society requires strategic decisions about energy and climate priorities now. The world has too few discretionary resources to investigate and develop all promising and potentially important energy and climate science opportunities. Instead we must target the top priority science outcomes that will provide the foundation for the technologies that enable the global society we envision.

Based on the discussion above, the most important energy and climate outcomes we seek are

- Adequate supply of sustainable energy to enable rapid economic growth; lively international trade and exchange of people and ideas; the aggressive pursuit of discovery science and innovative technology development; and reliable and predictable access to and price for energy to enable long range strategic planning.
- Stable global climate, to avoid the high human and economic cost of climate disruption that will deplete discretionary resources and impede the forward progress of society.
- An international market for energy, mediating across countries, regions and energy carriers, that commoditizes energy, diversifies its supply, and promotes predictability of price through facile substitution of one carrier for another.

Prioritizing the science breakthroughs that will achieve these outcomes requires deep thinking and periodic reprioritizing as discovery science reveals the limitations of known routes and discovers new routes to the three targeted outcomes above. A fifty-year science vision should be bold rather than incremental, exploring the most valuable outcomes even if the route to implementing them is not yet fully understood [11]. With this criterion in mind, the key scientific discoveries that would realize the three energy and climate outcomes above are the following, sorted by increasing boldness.

- *In progress and sustainable:* renewable solar and wind electricity.
- *In progress but not sustainable:* nuclear electricity and shale gas.
- *Not yet in progress:* mineralization of carbon dioxide, electrical energy storage, recycling carbon dioxide to fuel, and interchangeability among chemical, electrical, thermal and photonic energy carriers.

3. The fifty-year time frame

Fifty years is the time required for major changes in the energy system [12], as illustrated in Fig. 1 for the traditional energy sources: wood giving way to coal for widespread steam power, oil enabling the internal combustion engine and distributed transportation, and natural gas carried inexpensively by an extensive pipeline network for residential and commercial heating and for powering industry. The next generation of energy sources, wind, solar and other renewables, hardly visible in Fig. 1, is at the very beginning of its market deployment

The fifty-year time scale for energy transitions emphasizes the importance of early and strategic decisions on new energy technologies. There is a significant incubation time to discover and integrate the materials and chemistry needed to empower new technologies, and for replacement of the infrastructure of the incumbent technology with that of the new.

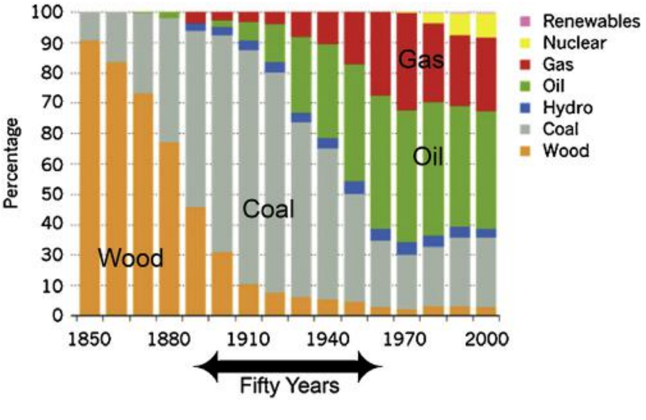


Fig. 1. Relative mix of energy sources in the United States. The timescale for transition from one fuel source to another is fifty years.
Source: Steven Chu and Arun Majumdar, Nature 488, 294 (2012).

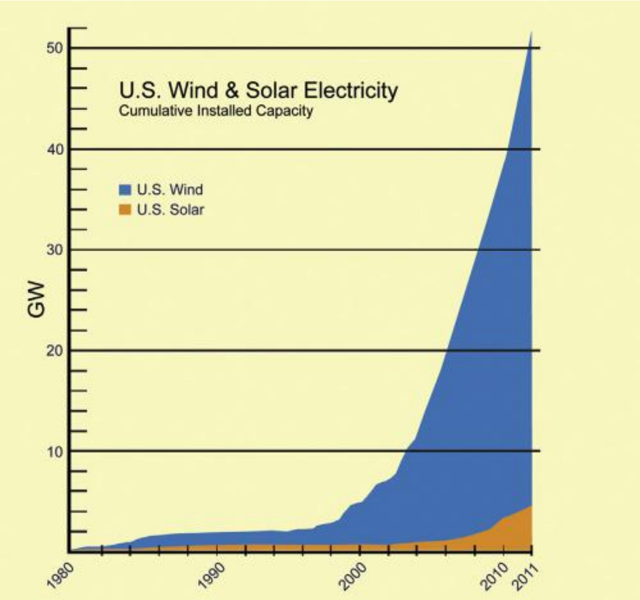


Fig. 2. Cumulative installed capacity of wind and solar electricity in the United States. Deployment is modest, approximately 2% of total US electricity use, with 30% or more annual growth in recent years. If the industries maintain 15% annual growth, deployment would grow to approximately 25% in 2030. *Sources*: SEIA, AWEA.

False starts are costly in depleting the limited discretionary resources available for basic energy research and development and in delaying the onset of transformational change. New directions must be evaluated not only on the technical and economic viability of the proposed technology, but also on the value of its contribution to creating a vibrant, interacting and rapidly advancing global society. Because discretionary resources for basic and applied energy research are limited, they must be prioritized strategically and deliberately directed to options with the greatest societal payoff.

4. Energy sources

4.1. Renewable solar and wind electricity

Solar [13] and wind [14] electricity are key technology directions supporting the first two priority energy outcomes outlined above. They are abundant resources [15–19] with potential that far exceeds our present global demand; they are capable of supplying much of the growing needs of developed and developing countries. The supply is reliable and predictable, widely accessible throughout the world and not subject to resource depletion or geopolitical constraints. Solar and wind electricity produce little or no climate-threatening carbon emission (other than initial construction and end-of-life recycling or disposal) and they displace carbon emissions from fossil electricity production, which now accounts for approximately 65% of total global electricity generation [20]. Solar and wind electricity are established and growing in Europe and the US, as illustrated in Fig. 2 showing the growth of US capacity since 1980.

The challenges for solar and wind electricity are lifetime and, for solar, efficiency. Even with recent dramatic reductions, the cost of solar PV without incentives remains significantly higher than fossil electricity [21]. Economies of scale and technology improvements will bring the cost down, though overcoming the large gap in cost between solar and other electricity technologies also will require significant science breakthroughs. Discovery and development of alternative materials besides silicon, development of thin film formats that require less material and increasing the efficiency of silicon alternatives have the potential to lower costs significantly below today's levels.

A major remaining opportunity for wind is tapping offshore resources, which are 50% steadier and stronger than onshore counterparts (see Fig. 3). Europe is a leader in exploring offshore wind technology, with projects in the North Sea demonstrating the opportunities and challenges. The lifetime cost of offshore wind is about twice that of onshore [21], due to the increased capital cost of constructing marine-based towers anchored to the sea floor, the increased cost of maintenance and access to offshore towers, and the corrosive environment of sea air and water. The solution to these challenges is maximizing the power output from each offshore wind tower. The size of the largest conventional wind turbines has risen from below a megawatt before 2000 to five megawatts today, limited by the weight that can be supported by a tower. High capacity wind turbines constructed of superconducting wire offer a promising new route for offshore wind. The high electrical current densities of superconducting wire enable motors and generators with twice the power output at the same size and weight as those using conventional copper wire. Superconducting offshore wind turbines with ten megawatt or

Fig. 3. Offshore wind. Offshore wind is 50% stronger and steadier than land-based wind, and requires shorter transmission distances. Superconducting wire enables high output, low weight wind turbines, reducing the cost of offshore wind to competitive levels.
Source: Earthyreport.com

more capacity are well within technical reach [22]. The challenge is to raise the current carrying capacity and lower the cost of superconducting wire enough to make high capacity superconducting offshore wind turbines economically competitive. Achieving this basic science challenge would significantly increase the penetration of offshore wind.

4.2. Nuclear electricity and shale gas

Nuclear electricity [23] and shale gas [24,25] are examples of technologies that are already deployed at significant scale, are economically competitive, and are ready for scaling to greater commercial penetration. Nuclear electricity emits no carbon dioxide in operation and uranium resources, if spent fuel is reprocessed, can last many hundreds of years, providing electricity at prices competitive with fossil. Recoverable shale gas resources are abundant and widely distributed around the world [26] (see Fig. 4). The advent of shale gas on the US market has lowered the price by factors of two or more and is predicted to make up nearly 50% of the US supply by 2035 (Fig. 4). The abundance and low price of shale gas will transition the US from an importer to an exporter of natural gas [27], and it emits approximately a factor of two less carbon dioxide than coal and oil at its point of use [28]. These sustainable attributes satisfy the first three energy outcomes outlined above for a vibrant, interactive and rapidly advancing global society. Technically and economically, these two technologies are "ready to go."

The challenge with nuclear electricity and shale gas is their potential for harm to human health and the environment. Resistance to expanding these technologies comes not from government regulators or the business community but from the public itself. Both technologies satisfy existing government standards for safe operation, and both are economically appealing to for-profit businesses. Large segments of the public, however, feel that these two technologies threaten their health through the potential for nuclear accidents and toxic contamination of the water and air, and threaten the environment through release of radiation and toxins to ecosystems. Furthermore, nuclear electricity requires the safe long-term storage of toxic and radioactive spent fuel [29] for hundreds of thousands of years, a task for which there is no precedent. These two energy technologies are unusual, in that they meet the requirements of technical feasibility and economic competitiveness – major challenges for other alternative energy technologies – but fall short in public concern for human and environmental health.

The question is whether these technologies can be revised to meet public concerns for human and environmental health. Increased regulation of these technologies can enforce higher safety standards, but adds cost without increasing performance. In contrast, revising the technology through discovery and design of new materials and processes can enhance health and safety while also enhancing performance and lowering cost. Passively safe nuclear materials and designs that automatically shut down in emergencies and do not require external cooling or power inherently reduce the risk of serious accidents like Three Mile Island, Chernobyl and Fukushima Daiichi [30,31]. These and other science and technology solutions not only remove safety from the realm of fallible human decision-making but also enable higher performance and lower cost.

Beyond advanced safety, the next generation of nuclear reactors can operate at much higher efficiency, requiring fewer units to produce the same power. Present reactor technology dates from the 1960s and operates with an efficiency of approximately 34%; modern materials and designs can perform at significantly higher levels. Higher efficiency requires higher neutron fluxes and operating temperatures, extreme conditions that demand new materials with designed nano- and mesostructures [32–34]. Many countries employ a "once through" fuel cycle that uses only ~4% of the uranium in a nuclear fuel rod before removing it and committing it to permanent storage [29]. Recycling spent nuclear fuel allows a much greater

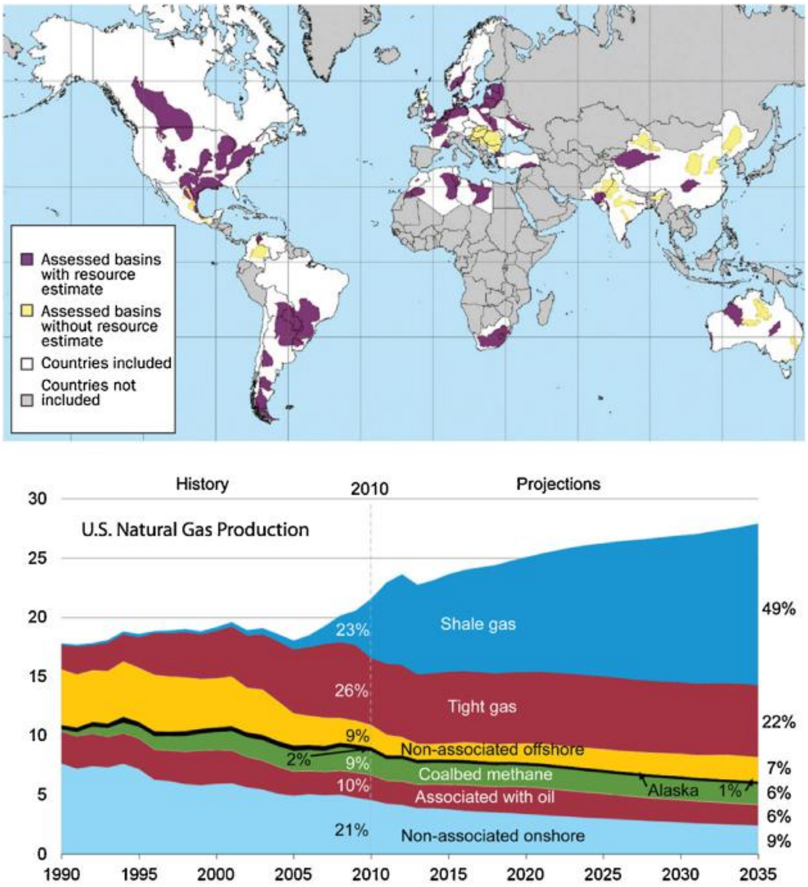
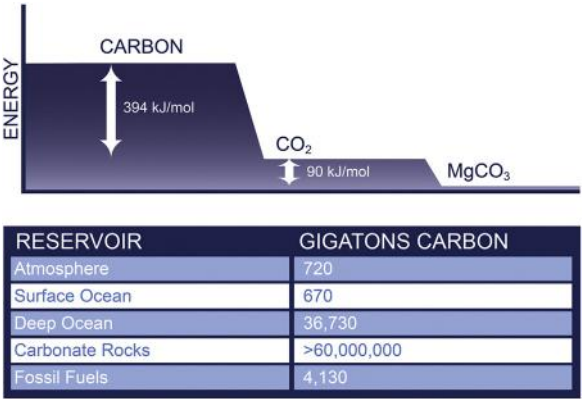


Fig. 4. Global shale gas distribution. World-wide distribution provides global access to fossil fuel supplies (upper panel). In the US, shale gas is rapidly becoming a dominant and inexpensive source of energy.
Sources: EIA, World Shale Gas Resources, http://www.eia.gov/analysis/studies/worldshalegas; and EIA, World Energy Outlook 2012.

fraction of the fuel to be used, significantly extending the useful life of earth's uranium resources, while reducing the volume of stored nuclear waste by a factor of four or more and the time required for storage from hundreds of thousands to thousands of years [35]. The challenges blocking expansion of nuclear electricity – accidents and the threat to human and environmental health – as well as the added benefits of higher efficiency, sustainable uranium fuel supply, smaller storage volume and shorter storage time, are better addressed as science and technology challenges rather than strictly regulatory challenges.

Shale gas presents a different set of sustainability challenges [36–39]. Some states in the US encourage shale gas development for its positive effects on increasing domestic energy supply, lowering energy prices, growing the economy and producing jobs. Europe has been less welcoming, citing contamination of air and water by migration of harmful fluids used in hydraulic fracturing through porous rock formations, acceleration of climate change due to increased leakage of methane to the atmosphere, and increased seismic activity caused by discarding toxic water recovered from fractured shale in deep disposal wells. Evidence for the detrimental effect of hydraulic fracturing on the environment and on community water supplies is growing [40,41]. In addition, hydraulic fracturing performs well below its theoretical potential. The initial rush of gas released by fracturing is temporary; within a few years the flow rate declines dramatically, ultimately releasing only $\sim$ 20% of the gas trapped in the shale seam. To be publicly acceptable, hydraulic fracturing must resolve the issues of its impact on human and environmental health. As with nuclear electricity, these issues can be addressed by increased regulation of existing technology, which increases cost without improving performance, or by advancing the science governing shale gas extraction to reduce its detrimental effects and simultaneously raise its performance.

The science issues of hydraulic fracturing are the fracture mechanics of rock and the flow of fluids through mesoporous rock formations [42,43]. Fracture of materials following an hydraulic shock is a complex sequence of defect creation, aggregation and re-configuration, starting with atomic displacements occurring on the timescale of picoseconds followed by migration and organization of defects into mesoscale structures which spawn cracks that propagate and grow into fractures on time scales from microseconds to minutes or longer. Predicting and ultimately creating targeted rock fracture patterns from initial hydraulic shocks require advances in in situ observation and computer modeling of crack formation and



RESERVOIR	GIGATONS CARBON
Atmosphere	720
Surface Ocean	670
Deep Ocean	36,730
Carbonate Rocks	>60,000,000
Fossil Fuels	4,130

Fig. 5. Carbonate rocks for carbon storage. Carbonate rocks such as magnesite ($MgCO_3$) are more stable than carbon dioxide, releasing ~90 kJ/mol of energy on formation (upper panel). The high stability of carbonate rocks makes them the largest carbon reservoir on earth, more than 1000 times larger than the deep ocean, the nearest competitor. Storing all the carbon emissions from combustion of all the fossil fuels on earth in carbonate rocks would increase their abundance by a negligible amount, less than 0.01% (lower panel).

Sources: Upper panel: Geoffrey F. Brent, Daniel J. Allen, Brent R. Eichler, James G. Petrie, Jason P. Mann, and Brian S. Haynes, Journal of Industrial Ecology 14, 94 (2011); lower panel: P. Falkowski, R. J. Scholes, E. Boyle, J. Canadell, D. Canfield, J. Elser, N. Gruber, K. Hibbard, P. Hogberg, S. Linder, F. T. Mackenzie, B. Moore III, T. Pedersen, Y. Rosenthal, S. Seitzinger, V. Smetacek, W. Steffen, Science 290, 291 (2000).

propagation. The flow of released shale gas through mesoscale fissures created by hydraulic fracturing is likewise poorly understood. Chemical reactions take place as fluids flow through nano- and mesoscale channels, closing or opening the pores depending on fluid and rock composition [44]. Advances in the fracture mechanics of shale seams and understanding the reactive flow of fluids in mesoporous media will address the threats to human health and the environment as well as raise the performance and lower the cost of the fracking process.

4.3. Mineralization of carbon dioxide

The fifty-year time scale for transformation of the energy system illustrated in Fig. 1 implies that fossil fuels and carbon emissions will remain significant features of the global energy system for many decades. If climate is to be stabilized, carbon dioxide emissions from fossil fuel combustion must be captured and stored or recycled to fuel. The most discussed storage approach is geologic carbon sequestration, where carbon dioxide is injected underground, flows through porous rock formations until it encounters an impenetrable barrier or neutralizes the driving gradient, and remains trapped underground for thousands of years without leaking to the atmosphere. Geologic sequestration faces several challenges, including monitoring the migration of the gas, transporting the gas to the storage site, the risk of leakage to the atmosphere, the effect of chemical reactions on the underground porous rocks, and legal and regulatory issues [45].

A much simpler and more stable storage solution is carbon mineralization – the reaction of carbon dioxide with metal oxides found in calcium or silicate minerals to form carbonate rocks [46]. The reaction is downhill, releasing rather than requiring energy, and carbonate rocks like limestone ($CaCO_3$) and magnesite ($MgCO_3$) are among the most stable minerals in nature [47] as illustrated in Fig. 5. Carbonate rocks contain more than a thousand times the carbon in the deep ocean and can easily accommodate all the emissions from combustion of all the fossil fuel on earth. The stability of carbonate rocks eliminates the need for post-storage monitoring and there is no risk of leakage back to the atmosphere. Carbonates like limestone are commonly used building materials and pose no threat to human health or the environment. Mineralizing carbon emissions eliminates the monitoring, leakage, environmental, legal and regulatory challenges of geologic carbon sequestration.

The science challenges of carbon dioxide mineralization are slow reaction rates and non-reactive surface coatings on the calcium or silicate mineral feedstocks for the carbonation reaction. These are classic science challenges: finding catalysts for targeted chemical reactions is a more-than-century-old theme of chemistry, and controlling the surface chemistry of materials is likewise a highly developed endeavor. These challenges have science solutions with the potential to bring mineralization of carbon dioxide within technical and economic reach.

4.4. Electrical energy storage

Electricity has many attributes of a sustainable energy carrier. Once produced, it is efficient, environmentally benign, adaptable to a diversity of end uses and leaves no physical or chemical evidence of its use. Generators, motors and the electricity grid all operate at greater than 90% efficiency; and electricity powers a diversity of end uses including lighting, refrigeration, urban trains, communication, medical diagnosis, and entertainment. Electric cars may bring a major new use for electricity with the potential to displace significant amounts of foreign oil.

The unsustainable aspects of electricity as an energy carrier are its production by fossil fuel combustion, and the necessity of instantaneous balancing of production and demand. Fossil fuel combustion for power generation is only 35% efficient and emits 34% of US carbon emissions, along with a host of harmful and toxic pollutants from extraction and refining of the raw fuels. Instantaneous balance of production and demand is traditionally accomplished by ramping nimble generation like gas or hydroelectricity up or down and keeping turbines active but disengaged as ‘‘spinning reserve’’ to accommodate rapid variations in demand. Reserve plants are usually the dirtiest, least efficient and most expensive to operate, used only marginally to meet demand peaks. The use of these dirty, inefficient plants significantly lowers average efficiency and raises average carbon emissions. The variation in demand from the highest peak on a summer afternoon to the lowest valley on a winter night is typically more than a factor of two, requiring significant capital expense for generation and transmission equipment that is idle much of the time.

The advent of significant penetration of wind and solar plants adds a new dimension to instantaneous balancing: uncontrollable generation side variability. Although wind generation is typically predictable on monthly time scales, it is quite unpredictable on daily timescales [48]. There are usually one or more days in every month when the wind is calm for 24 consecutive hours. Solar generation is compromised by clouds, which reduce output by 70% on overcast days. Today’s small percentage of wind and solar penetrations allow these generation variations to be accommodated easily by traditional techniques. At larger penetrations of 20–50%, however, wind and solar variations must be accommodated by other means, such as building a backup gas generation plant of similar capacity for each wind or solar plant, or implementing utility scale electricity storage to smooth the generation peaks and valleys. By replacing inefficient, polluting and resource-depleting fossil fuel combustion with renewable solar and wind generation and by backing up renewable generation with electricity storage instead of gas generation plants, electricity can move toward becoming a sustainable energy carrier.

Electric cars provide a second incentive for advancing electricity storage: extending driving range to exceed the commuting and personal needs of most drivers. The battery for the Chevy Volt occupies a substantial fraction of the volume of the car (Fig. 6). Despite the high efficiency of its electric motor, the driving range of the Volt on a full charge is only 38 miles [49,50], too short for the daily needs of many drivers. The Volt extends driving range by providing a gasoline engine to charge the battery when needed, reminiscent of the conventional natural gas turbines used to back up solar and wind power. A substantially larger energy density for batteries is needed if electric cars are to achieve widespread penetration. A factor of five would bring the 38-mile range of the Volt to approximately 200 miles; large enough to comfortably serve the daily commuting and personal needs of many drivers.

The impressive increases in energy density of lithium ion batteries – averaging 5% per year over the last two decades [51] – are not sufficient to enable back up of renewable electricity generation or to create a substantial market for electric cars.

Fig. 6. GM Volt car and battery. The battery that powers the Chevy Volt occupies a significant fraction of the volume of the car. A full charge enables driving 38 miles.
Source: General motors.

The factor of five improvement needed to achieve these goals requires battery technology beyond lithium ion [52]. Three approaches are promising: multivalent intercalation [53], where the monovalent lithium ion is replaced with a divalent or trivalent ion; replacing low energy density intercalation with high energy density chemical transformation [54], and developing a new generations of flow batteries [55].

Each of these discovery science approaches explores an innovative new direction in high capacity electricity storage that is capable of making electricity a sustainable energy carrier through widespread deployment of renewable electricity, and of replacing significant amounts of unpredictable foreign oil with secure, domestic electricity for transportation. These science and technology objectives for electricity storage directly support the first two energy outcomes for a vibrant, interactive and rapidly advancing global society: abundant, inexpensive and sustainable supply; reliable and predictable access and price; and stable climate through reduced carbon emissions. Advanced electricity storage supports the third energy outcome as well, allowing electricity to substitute for oil in transportation, a necessary first step in creating an international market for energy that mediates among countries, regions and carriers of energy.

4.5. Recycling carbon dioxide and water into fuel

Chemical fuels are historically unsustainable energy carriers. Fuels are used in a sequence of once-through processes, starting with extraction from the earth, refining to separate targeted end-use fuels from the extracted mixture, combustion to produce heat, and release of combustion and refining products to the earth or atmosphere. These once-through processes deplete the fossil resource and replace it with carbon dioxide that causes climate change and coal ash and refining residues that are harmful or toxic to humans and the environment.

The once-through chemical fuel sequence, however, can be converted to a sustainable process by recycling the combustion products, carbon dioxide and water, to fuel using renewable energy. This sustainable cycle requires no additional feedstocks and uses the same chemical ingredients over and over, changing their form twice on each cycle, once on combustion from high-energy fuel to low energy carbon dioxide and water and a second time on regeneration from carbon dioxide and water to fuel driven by energy from the sun. Corn ethanol was once thought to be a sustainable chemical fuel: the carbon dioxide and water combustion products could be recycled through the ecosystem to grow a fresh crop of corn, which is then fermented into ethanol to complete the cycle. We now know that the fossil fuel and carbon emission footprints of tilling the soil, and planting, fertilizing, harvesting, transporting and fermenting the corn to ethanol are approximately equal to the direct combustion of the gasoline equivalent of the ethanol produced [56]. This route to recycling carbon dioxide and water to chemical fuel is not sustainable.

A second route to sustainable chemical fuels appeared in earnest in approximately 2003: hydrogen as a fuel [57,58] (upper panel, Fig. 7). In this approach, hydrogen supplies on-board fuel cells to produce electricity for electric cars, producing only environmentally benign water and a modest amount of heat as by-products. Achieving sustainability by recycling water to hydrogen is a central challenge, however. Most hydrogen in use today comes from reforming methane via the water-gas shift, a once-through process that depletes fossil resources, produces carbon emissions, and is itself not sustainable. Recycling can be accomplished by electrolysis of water, which closes the fuel cycle but is not sustainable if the electricity for electrolysis comes from fossil sources. Electrolysis using solar or wind electricity is sustainable, and a more advanced proposal splits water by photoelectrochemistry [59], where sunlight creates electrons and holes in a semiconductor which then drive chemical reactions such as water splitting. These approaches to creating a sustainable chemical fuel cycle based on hydrogen are scientifically sound; they await the discovery, design and development of materials and chemistry needed to achieve them at competitive cost.

A third route to sustainable chemical fuels is reforming the cellulose in plant leaves and stalks to chemical fuel (middle panel, Fig. 7) Cellulose is much more abundant biologically than fruit such as corn, but requires more elaborate and expensive processing to convert to alcohols and other fuels compared to the simple fermentation of corn [60,61]. Cellulosic ethanol began to be pursued aggressively in about 2007. The approach is a significant improvement over corn ethanol, replacing corn with much more abundant cellulosic feedstocks. The scientific challenge is to develop the chemical processes to achieve conversion of cellulose to fuel at competitive cost. If successful, cellulosic ethanol could replace up to 30% of transportation fuels with sustainable chemical energy carriers [62].

A more comprehensive approach to sustainable chemical energy carriers is recycling carbon dioxide and water to fuel without relying on biology [63–65] (lower panel, Fig. 7). As in cellulosic ethanol, the energy source for the reforming process is the sun, tapped through solar or wind electricity, and implemented in an integrated photoelectrochemistry process, or through high temperature reactions in a solar furnace [66] The advantage over cellulosic ethanol is capacity: 100% of transportation and other fossil fuels can be replaced, using a stock of carbon dioxide and water molecules that recycle continuously between fuel and combustion products. This approach requires carbon dioxide to be recovered from the air, to enable capturing the exhaust of cars and trucks for recycling.

The appeal of non-biological recycling of combustion products to fuel, and the potential for its success, are the many routes for chemically recombining carbon dioxide and water to fuel (Fig. 8). Unlike the limited routes for reforming water to hydrogen, there are a host of reaction routes and end-use chemical fuels that are producible from water and carbon dioxide feedstocks. This rich horizon of possible recombination routes and end-use chemical fuels independent of biology is the promise and the potential for realizing a sustainable chemical energy carrier.

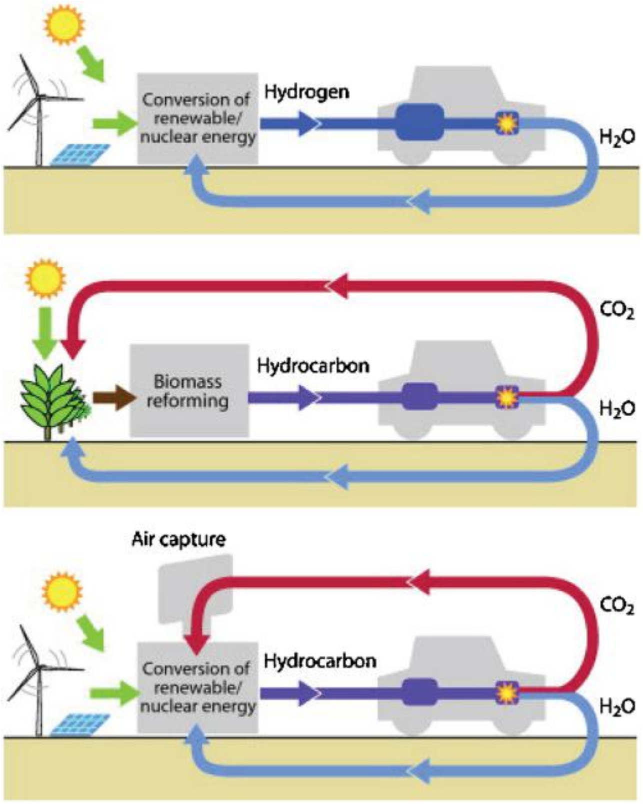


Fig. 7. Routes to creating a sustainable chemical fuel carrier. Upper panel: hydrogen as a fuel creates water as the only output, requiring electrolysis or photoelectrochemistry using solar energy to regenerate. Middle panel: biofuels produce carbon dioxide and water as outputs, recycled through biological photosynthesis to cellulose and then refined to fuel. Lower panel: replacing biological photosynthesis with chemical reprocessing eliminates cellulose from the recycling loop and enables direct production of a wide variety of hydrocarbon fuels.
Source: Graves, Ebbesen, Mogensen, Lackner, Renewable and Sustainable Energy Reviews 15, 1 (2011).

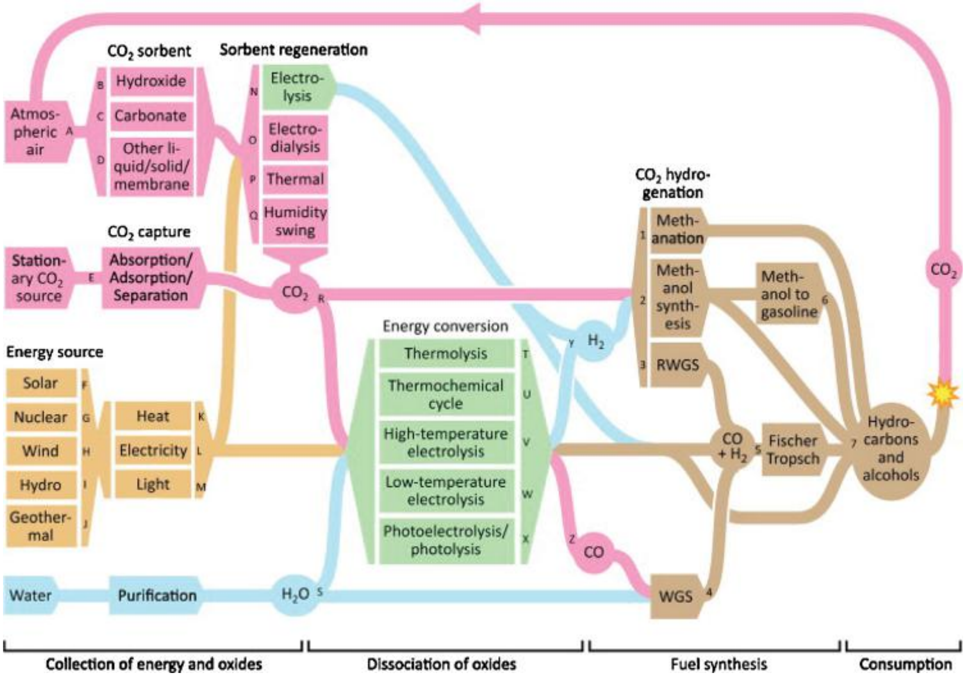


Fig. 8. Creating hydrocarbon fuels. Chemical reprocessing of carbon dioxide and water can proceed by a diversity of routes to produce a host of hydrocarbon fuels.
Source: Graves, Ebbesen, Mogensen, Lackner, Renewable and Sustainable Energy Reviews 15, 1 (2011).

4.6. Interchangeable energy carriers: chemical bonds, electricity, heat and light

The third energy outcome, an international market in energy that mediates among countries, regions and energy carriers, allows easy substitution of one energy carrier for another. Such a market creates multiple options for achieving energy goals and for preventing unexpected shortages of a single energy source from having outsized impact on the orderly operation of global energy, economic and social systems. An international market commoditizes energy, giving it wide flexibility across carriers to better serve societal needs and to increase the reliability and predictability of access to energy.

Three energy carriers have been discussed above: electricity, heat and the chemical bonds in fuels. Light is the fourth basic energy carrier, the most important because it provides earth with its primary energy input: sunlight. Sunlight drives earth's derivative energy systems, including wind, rain, river and ocean currents, and photosynthesis of organic matter that becomes food for animals, raw material for geologic fossil fuel formation and feedstock for biofuel production. Sunlight is earth's largest energy source, dwarfing all the derivative sources by a wide margin. Tapping sunlight directly and converting it to the other carriers – electricity, heat and chemical bonds in fuel – is the ultimate source of accessible, reliable and predictable energy.

Facile interchangeability among energy carriers needs to advance beyond the present status. Heat is a common intermediate in energy conversion among carriers, as in combustion of fossil fuels to drive electrical generators. Combustion and heat, restricted by Carnot thermodynamic limits, are typically only modestly efficient when employed with ordinary temperature gradients. Higher efficiencies can be achieved with electrochemical conversion of chemical fuel to electricity, operating without large temperature gradients and near ambient temperature. The highest commercially available efficiency for converting sunlight to electricity is slightly larger than 20% in single crystal silicon solar cells, far lower than the theoretical limit of 60% or more. The conversion of sunlight to chemical fuel operates well below its theoretical limit: it is typically less than one percent for biological plants and the best artificial photosynthesis. These low conversion efficiencies leave ample headroom for science and technology to improve conversion performance.

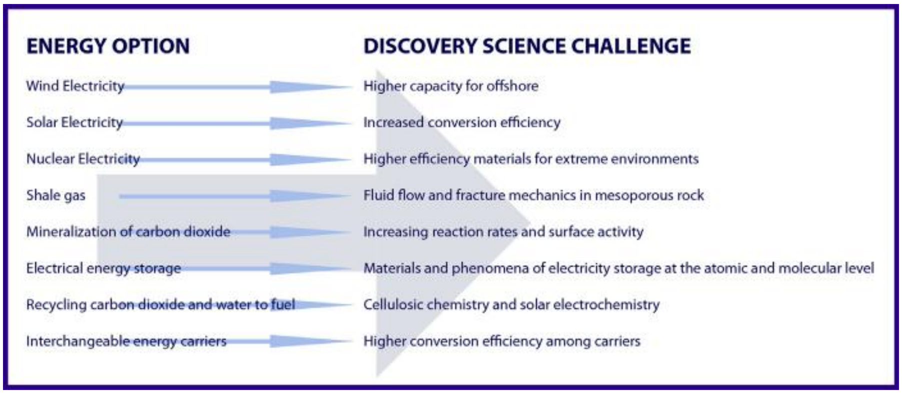
5. Discovery science, innovation and cost

In prioritizing energy outcomes that will drive a vibrant, interactive and rapidly advancing global society, the relative cost of discovery, applications development and commercial deployment must be kept in mind. Discovery is relatively inexpensive, requiring small quantities of materials and exploring phenomena on the scale of a scientific laboratory. Once a promising set of materials and chemistry is identified, a much more expensive process of applied science and development begins, to assemble an integrated technical system and to demonstrate a pilot operation capable of being scaled to commercial proportions. The final stage of deployment of a working technology is the most expensive, requiring manufacturing, assembly, and deployment of a critical mass of units to realize economies of scale and reach the tipping point of commercial viability. The conventional rule is that if discovery costs $1, then applications development costs $10 and deployment costs $100.

Given these cost scales, society can afford to explore many promising discovery directions but only a few applications development and commercial deployment opportunities. The cost of discovery and follow-up learning about a new material or chemistry is small compared to the benefit: a knowledge base useful not only for the material or chemistry at hand, but also as an intellectual resource for launching subsequent exploratory directions and for integrating the discovered material or phenomena into future technologies. Discovery science stimulates innovation, the foundation of competitiveness and enduring economic growth. It reveals what applications will fail before the much bigger investments in development and deployment are made. It pays back much more than it costs – economists estimate that half the economic growth since World War II is due to innovation coming from scientific discovery. Importantly, it primes the innovation ecosystem, the network of risk taking, creativity, entrepreneurship, and business savvy that drives the leading edge of the economy. Society's discretionary resources for discovering and developing new energy technologies rise and fall with the economic times. In good times and bad, however, discovery science and follow-up learning are among the least expensive and highest payoff investments that society can make.

6. Conclusion

A major theme of this article is the critical role of today's energy decisions in determining the kind of global society we will realize in fifty years. An adequate, inexpensive and sustainable supply of energy, reliable and predictable access to that supply, a stable climate, and a transparent international energy market mediating across countries, regions and energy carriers are top energy priorities for a vibrant, interactive and rapidly advancing global society. Because discretionary resources available for developing new energy technologies are limited, energy outcomes that promote these basic societal goals must be deliberately identified, prioritized and strategically pursued. The energy outcomes presented here are chosen first for their essential contribution to a vibrant, interactive and rapidly advancing society, and second for their scientific and technical achievability over a fifty-year time scale (Fig. 9). The outcomes include two technologies (wind and solar electricity) already on the road but in need of further discovery in materials and chemistry to achieve widespread penetration, two that are on the road but need significant discovery to become more sustainable (nuclear electricity and shale gas), and three that are not yet on the road and need substantial discovery in materials and chemistry to be ready for



ENERGY OPTION	DISCOVERY SCIENCE CHALLENGE
Wind Electricity	Higher capacity for offshore
Solar Electricity	Increased conversion efficiency
Nuclear Electricity	Higher efficiency materials for extreme environments
Shale gas	Fluid flow and fracture mechanics in mesoporous rock
Mineralization of carbon dioxide	Increasing reaction rates and surface activity
Electrical energy storage	Materials and phenomena of electricity storage at the atomic and molecular level
Recycling carbon dioxide and water to fuel	Cellulosic chemistry and solar electrochemistry
Interchangeable energy carriers	Higher conversion efficiency among carriers

Fig. 9. Summary of energy sources and discovery science challenges.
Source: Authors.

development into technologies capable of reaching competitive status (mineralization of carbon emissions, electricity storage beyond lithium ion batteries, and recycling carbon dioxide and water to create a sustainable chemical energy carrier).

A transparent and orderly international market in energy mediating among countries, regions and energy carriers requires not only economic, social and political structures but also discovery science and technology to enable facile conversion of energy from one carrier to another. This interchangeability among energy carriers would fully commoditize energy and increase the flexibility, reliability and predictability of the energy access chain. Discovery science and follow-up learning about new materials and chemistry is a factor of ten less expensive than the applied development and demonstration of new technologies based on these discoveries, and a factor of one hundred less expensive than commercial deployment of new energy technologies. Discovery science is an especially important societal investment for its relatively low cost, its stimulation of innovation, its identification of false starts before expensive development directions are launched, its payback of much more than its cost in economic growth, and its priming of the innovation ecosystem. Unlike increased regulation alone, discovery science addresses threats to human and environmental health while simultaneously lowering cost and increasing performance of energy technologies. In good and bad economic times, discovery science is high priority for its enduring value in promoting a vibrant, interactive and rapidly advancing society.

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