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Introductory Lecture 1:

Scientific and Technical Challenges in Electricity Generation

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Three renewable energy technologies for power systems – photovoltaics, wind, and solar thermal – are discussed. Based on world-wide experience with these systems, methods of improving efficiency, reliability, and cost for commercial electricity generation are described.

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1. Introduction

Renewable energy sources are the oldest known to mankind. But it was not until the oil crises of the 1970s that we began a thorough scientific investigation of the renewable energy technologies. Renewable energy presently makes significant contributions to the world's energy needs. In the United States for example, renewable energy provides more total energy than all of America's nuclear power plants.

One cannot generalize about the renewable energy technologies without the loss of accuracy. Therefore my introductory lecture will focus on several specific technologies that are used to generate electricity. The IEA report, *Renewable Sources of Energy* was issued in March of 1987. That report classified the renewable energy technologies based upon their technical and economic status. Today I will discuss photovoltaic power systems, wind power systems, and solar thermal power systems. All of these were classified by the IEA report as «Under-Development», which was defined as «technologies which need more development to improve efficiency, reliability or cost so as to become commercial».

In the following, I will describe each technology, give some specific accomplishments and the present status of some operating systems, and then emphasize selected challenges facing the technologies. I will close my presentation by briefly discussing requirements the utilities have and how the renewable energy technologies are meeting those requirements.

By choosing these three technologies I do not mean to imply that they are the more important than some others. They are however, representative of the progress being made in electricity-producing technologies.

I chose to focus on electricity because it is the one energy form whose use remains

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positively correlated with economic growth. The United States of America and most IEA countries have significantly reduced their per capita consumption of other forms of energy. The use of electricity continues to grow because most of our modern conveniences, the modern miracles of technology, depend upon electricity for their power – from washing machines to microwave ovens to computers.

If we provide electricity to the lesser developed nations of the world, we accomplish two very important things simultaneously. We provide the energy to allow them to raise their standard of living. In so doing we will also develop larger markets for the modern conveniences which most IEA countries manufacture and export. In that sense the energy-producing technology that we can manufacture and export should be viewed as the first step to a much larger world market for all of the developed countries of the world.

So where do these technologies stand now and what remains to be done before they are indeed commercially viable?

2. Photovoltaics

2.1. Technology Description

The photovoltaic (or solar) cell is part of the «solid-state revolution». Its operation follows the basic principles of solid state and quantum physics, with sunlight directly generating DC electricity.

The smallest element of a photovoltaic (or PV) system, the solar cell, has two or more specially prepared layers of semiconductor materials whose atoms absorb light, freeing electrons to carry electric current. A junction between the two dissimilar semiconductor materials creates a voltage that drives the electrons through the circuit.

An individual cell produces a small amount of power. Therefore, many cells are connected into *modules* to provide more power, voltage, current, and protective packaging for the cells. For larger power needs, modules can be grouped together to form *arrays*.

Modules fall into two broad categories. *Flat-plate* modules use large areas of cells under regular sunlight. *Concentrators* use relatively expensive, high-efficiency, small-area cells, and low-cost lenses that concentrate sunlight onto the cells, and trackers to follow the sun through the sky.

The direct current generated by a PV system can be used as is, but it is usually converted to AC electricity. The electricity may then be used to power an AC load or be fed into a utility interface.

Solar cells are made in two basic configurations: single-junction or multi-junction. A *single-junction* cell can only be optimized for a small portion of the solar spectrum. What portion it is optimized for is determined by the choice of semiconductor materials. Consequently, a single-junction cell has limited conversion efficiency. *Multi-junction* cells, used primarily in concentrator systems, are designed to overcome this limitation. In a multi-junction device, cells tuned to different portions of the solar spectrum are stacked. This allows a multi-junction device to absorb a broader spectrum of sunlight, and hence produce more electricity, than a single-junction cell.

2.2. Status

In the last twelve years, the technology of photovoltaics has made great strides. In 1975, electricity generated by photovoltaics cost almost $ 10 per kilowatt-hour. Today, that price is 25c to 30c per kilowatt-hour, a reduction of more than 40fold. Such a dramatic improvement has been made possible largely because of the progress made in photovoltaic materials. There are dozens of materials being used to make photovoltaic devices. I will discuss just a few of the more prominent: crystalline silicon, amorphous silicon, polycrystalline thin films, and so-called III-V materials.

Crystalline silicon is the pioneer material of both the photovoltaic and the semiconductor industries. It is the best understood of the photovoltaic materials and is still being improved, recently achieving efficiencies in excess of 22% under normal sunlight and 28% under concentration. This is double the efficiencies of 12 years ago. The reliability of crystalline silicon modules has also progressed impressively. Twelve years ago modules were lucky to last 5 years. Today, projections are that they will last 30 years. Crystalline silicon devices, however, do have their disadvantages: they require a lot of material, a lot of energy to make, and are not easily adaptable to mass-production techniques.

Amorphous silicon has become almost as widely used in photovoltaics as crystalline silicon. Its technology and industrial bases are large and growing and its markets are about equal to those of crystalline silicon. The major advantage of amorphous silicon is that it can easily be deposited as a thin film and low-cost substrates such as glass or plastics. This makes it inexpensive and amenable to mass-production techniques. Entire modules can be deposited in one process. Since its discovery as a photovoltaic material more than a decade ago, the efficiencies of amorphous silicon devices have risen dramatically. Experimental small-area devices are nearing 13% efficiency while laboratory modules have achieved 10%. In spite of the advances, low efficiency is one of the major limitations of amorphous silicon. Although we have measured some as high as 8%, most commercial modules are presently around 5% to 6% efficient. Amorphous silicon devices also lose some efficiency when exposed to sunlight and have not yet demonstrated long lifetimes.

Polycrystalline thin film materials, such as copper indium diselenide and cadmium telluride, have many of the advantages of amorphous silicon and they are rapidly improving. In fact, one of the more exciting recent breakthroughs was a square-foot copper indium diselenide module that was 11.2% efficient. These materials tend to be photo-stable, especially $CuInSe_2$. But they are still relatively new and do not have a very large technology or industrial base.

Gallium arsenide and other materials from Groups *III and V* of the Periodic Table and their alloys, such as gallium aluminium arsenide, are also widely used or researched. Some of these materials, like GaAs, have a long history and a relatively wide science and technology base. Their special attraction is their promise for very high efficiencies. They have recently achieved 24% efficiency under unconcentrated sunlight and 31% efficiency under concentrated sunlight. In a three-junction design, III-V materials promise efficiencies as high as 40%. Devices made of III-V materials and their alloys, however, can be difficult and expensive to make.

2.3. Applications

Thirty years ago, the only practical PV application was to power satellites in space. Although PV is still the power of choice for satellites, today the profusion of PV materials is matched only by the rapid growth of PV applications. PV systems are being used for applications needing milliwatts of power to megawatts of power.

At one extreme are tiny cells, weighing less than 36 milligrams, used for tracking honey bees. At the other – ARCO Solar's 6.6 megawatt system that supplies electricity to a utility in Southern California. In between are systems that power calculators and wrist watches, pump water and irrigate land, refrigerate vaccines, power cars, such as those that competed in the trans-Australia race, power communications, and provide electricity for residences.

Together, these applications have spawned an international market that is nearing $ 300 million a year. But to have a major impact on the international markets and on energy supplies, PV still has to become more competitive, especially to enter the utility-scale markets. To do this, photovoltaics must overcome three hurdles. The technology, especially some of the newer materials, will have to show long-term *lifetime* and reliability. *Cost* will have to decrease and *efficiencies* need further improvement.

To make photovoltaics more competitive, the U.S. National Photovoltaics Program is working on each of these hurdles to reach the short-term goal of 12c per kilowatt-hour and the long-term goal of 6c per kilowatt-hour. This extra three- or fourfold reduction in cost appears achievable. But to get there requires meeting several scientific and technological challenges. I have selected a few of the more important ones to discuss.

2.4. Scientific and Technological Challenges

Perhaps the best scheme to understand the challenges is to divide them into: lifetime, cost, and efficiency. In addition, due to the maturity of single-crystal silicon, I will limit my discussion of the challenges to thin films and multi-junction.

Lifetime: Thin-film modules need the same reliability that single-crystal silicon is approaching – 30 years lifetime with little degradation in performance. Problems with thin-film modules include delamination and deleterious effects due to daily heating and cooling cycles. But the major concern is with encapsulation. Most companies use a plastic encapsulant specially developed for the modules. Nonetheless, almost all companies are experiencing problems with moisture, which results in corrosion. We need to improve our encapsulation materials and techniques to reduce the moisture and eliminate the corrosion. At the same time, however, we cannot afford to increase the cost of the modules.

Cost: The major challenge with cost is scaling up to produce larger-sized thin-film modules while maintaining conversion efficiencies. We need to scale-up reactors (chemical vapor deposition, electrodeposition, or physical vapor deposition) so that we can produce modules as large as 30 m^2. At the same time, the reactors must be in-line, automatic, and low cost. Doing this would allow a reduction in the cost of PV generated electricity to 10–12 c per kilowatt-hour. Achieving this involves the engineering problems of simultaneously controlling several important parameters. A thin-film device contains several layers of different materials with exacting properties. And the layers are often on the order of 50 to 200 Å thick. This means that depositon of the materials must be uniform and precisely controlled.

The problems with reactors of commercial size are: depositing uniform, high-quality layers; obtaining large yield and throughput (as much as 1 million square meters per year per reactor system); minimizing waste; understanding and controlling gas flow dynamics; controlling material species and ratios, especially at the many interfaces, where the species tend to mingle; understanding and controlling chemical reaction kinetics; and, for electrodeposition processes, controlling currents in electrolytes.

For multi-junction configurations, the problems multiply. There are more layers, more materials in differing proportions, and more interfaces where intermingling of species can occur.

Efficiency: To meet the long-term goal of 6 c per kilowatt-hour, photovoltaic modules must not just be long-lived and inexpensive to make, they must also become more efficient. We are trying to increase the efficiency of all photovoltaic materials. But we feel that most can be gained with advances in thin films and high-efficiency concepts.

For *thin-films* technology we would like to get to 15% module efficiency. With respect to *amorphous silicon* at least two things stand in the way of meeting this goal. The first is the phenomenon known as the Staebler-Wronski effect, where the efficiency of a-Si:H cells deteriorates 10% to 20% after initial exposure to sunlight. We are studying the effect and are searching for ways to reduce or eliminate it. Second, to achieve 15% module efficiency with a-Si will require multi-junction concepts. One of the leading candidates is a 3-junction concept that uses germanium and carbon alloys of amorphous silicon. The problem is, we cannot yet produce top-quality alloys that can be reproducibly and monolithically fabricated in a three-junction device.

With *copper indium diselenide* there are also two major barriers to reaching 15% efficient modules. The first is that Cu In Se_2 has an unexpectedly low open-circuit voltage. Two things that increase the open-circuit voltage are the inclusion of gallium ($CuInGaSe_2$) and baking the cell in oxygen. However, we still do not understand either the role of oxygen or gallium. Second, as with a-Si, to reach 15% efficiency we will need to rely on multi-junction concepts. And as with a-Si, the difficulty lies with the materials and alloys. Specifically, one of the more promising structures is a three-junction device that uses a cadmium telluride alloy as the top cell. But we have yet to develop a sufficiently high-quality CdTe alloy.

With *high-efficiency concepts*, we intend to build two- and three-junction devices that can achieve efficiencies as high as 35% to 40%. Presently, we are investigating III-V materials and their tertiary and quaternary alloys.

There are two basic ways to make multi-junction devices. You can make the individual cells separately and mechanically stack them. Or, you can monolithically grow the multiple layers as a single device, which many consider to be the most promising strategy in terms of eventual simplicity, cost, and efficiency. With either approach, however, problems occur.

With each approach there are problems with control and reproducibility. Procedures to make the devices are extremely complicated. There are many layers of materials, many sources of materials, a multiplicity of flow rates, varying material ratios, and so on.

Mechanically-stacked devices also have problems with current matching and optical coupling. Inability to match the currents of constituent cells in a multi-junction stack can either complicate design and fabrication procedures or can hamper conversion efficiencies. The inability to attach cells in a stack while maximizing the transmission of sunlight throughout the stack can also hurt efficiencies.

With monolithically grown devices, on the other hand, a major barrier is presented by the need to match the lattices of the active cells in the stack. The lattice constants of most optimally paired cell materials do not match. This mismatch can cause defects when one cell is grown on the other. To circumvent these defects, it is often necessary to use many finely graded layers of materials. This further complicates fabrication procedures.

Even with these difficulties, however, progress is continually being made in high-efficiency concepts. In fact, the latest advance in efficiency, a jump of an absolute 3% over previous records, occurred within the last month. And the previous record was set only a few months prior to that.

3. Wind

3.1. Technology Description

Winds are created by the sun's unequal heating of the earth's surface and atmosphere and by the regional differences in pressures that result. Major wind patterns are global and regional. Complex local patterns also develop, influenced by local terrain and by natural and man-made obstacles. Thus, wind turbine technology involves very complex aerodynamic phenomena.

When the wind flows through the area swept by the rotor blades of a wind machine it sets the rotor in motion. For steady-wind conditions – when the wind is moving at a constant speed and direction – the rotor blade shape is designed to create lower pressure on the top of the blade and higher pressure on the bottom. The net difference in pressure generates aerodynamic lift, causing the rotor to turn. The rotating blades drive the gearbox and generator, which produces electricity. The available wind power is proportional to the capture area, the density of the air, and the cube of the wind speed. Unfortunately «steady-state-wind» is a theoretical construct that nature ignores.

Understanding the complex phenomena created by the interaction of a wind machine with the atmosphere relies on the science of wind turbine dynamics, which includes research in (1) atmospheric fluid dynamics, addressing complex wind patterns and turbulence; (2) aerodynamics, concerned with the interaction between atmospheric flow and the turbine's rotor; and (3) structural dynamics, concerned with the loads or stresses on the components of a wind system.

A wind machine contains five basic subsystems: (1) a blade or rotor, which is the energy capture device; (2) a drive train, usually including a gearbox and generator; (3) a tower; (4) turbine supporting systems, including controls and electrical cables; and (5) «balance-of-station» subsystems, such as ground support equipment and interconnection equipment.

Wind machines vary greatly in size, from those producing a few kilowatts to one which produces more than four megawatts of electricity. The average size of machines in wind farms today is between 75 and 150 kW. But manufacturers are increasing the size of their next generation machines to 100–250 kW. There are many possible configurations for wind machines. The type of machine we rely on mostly today is the horizontal-axis wind machine. But the past has also seen many exotic designs, including the tornado concept and the dynamic inducer.

3.2. Status and Applications

Since the mid-1970s large strides have been made in wind technology. Improvements in the cost, performance, and lifetime of wind machines have reduced the cost of wind-generated electricity more than tenfold, from more than $1.50 per kilowatt-hour to between 8c and 12c per kilowatt-hour. The reduction in cost and improved reliability are big reasons for the dramatic rise in wind-generated electricity in the United States of America and in growing interest worldwide in wind energy. The goal of the U.S. program is to reduce the cost to 4 c per kilowatt-hour. This will make wind energy systems competitive with conventional utility power.

Although wind energy systems can be used for dispersed applications, in the United States most are in wind farms in the state of California. There, they are used as supplemental power for utilities. The state has nearly 2 gigawatts of capacity, almost all of which has been installed since 1980.

To make wind machines more competitive on the utility market, we must increase their availability and their life expectancy. Availability is defined as the percentage of time a wind machine produces power when the wind is blowing at the machine's rated speed. Over the last decade we have increased the average availability to 85%. Although today some of the best machines are achieving 95% availability, we need to increase the *average* availability to 95%.

Most of the primary components of a wind energy system (tower, generator, gearbox) are rated at a 30 year *life expectancy*. But the rotors are lasting less than 5 years. To be competitive, we must make rotors that will last 20–30 years.

3.3. Scientific and Technological Challenges

In wind energy there are two major interrelated challenges. The first and largest challenge is *to understand the loads on the blades*. This is a very complicated problem. The resource is the wind. It is both turbulent and random in time and space. The everchanging wind causes everchanging loads in the system. The «delta's» are sudden, random, and often large. This makes it impossible to optimize the design of the rotors. There are too many changing parameters and they are not complementary. If you design to optimize one parameter, you necessarily have a negative impact on another. So any design must be a compromise. Indeed, one must consider many factors in addition to the random resource, including the effects of gravity, the shape of the rotor, the fact that blades flex, blade and tower harmonics, and static and dynamic stall.

The second interrelated challenge is one of *systems engineering*. One has to optimize all of the various components and their complex interactions, while reducing costs and improving reliability. The biggest problem with not understanding the changing loads and being unable to predict or model them is that they are the major cause of blade deterioration on wind machines. If we could better understand the loads we could design better blades that would last longer. We are, however, making steady progress in this area.

4. Solar Thermal Conversion

4.1. Technology Description

Solar thermal systems are composed of three basic elements – concentrators, receivers, and converters. *Concentrators* use tracking lenses or mirrors to focus the sunlight onto a receiver. The receiver, which should have high absorptivity and low emissivity, converts the photon energy into heat in a fluid. The converter uses the heat to produce the end product, most often electricity.

There are two basic types of solar thermal systems. Those that concentrate sunlight to a low degree and high-concentration systems. The typical low-concentration system employs a parabolic *trough*, which uses parabolic mirrors in a trough configuration. The mirrors concentrate the sun up to 100 times onto a fluid-filled tube positioned along the line of focus in the trough. The heat produced is from 100 °C to 400 °C and is used primarily as process heat, although it is also being used to generate electricity. Troughs are modular, and many can be grouped together to produce more heat or power.

Parabolic troughs are a proven technology. By the end of this year Luz International, Ltd, for example, will have installed 6 or 7 cogenerating plants in Southern California, for a total capacity of nearly 200 million watts. They are using the parabolic troughs for 75% of the steam heat. Then, using natural gas for the other 25%, they generate electricity, which they sell to a local utility.

One kind of high-concentration system is the *dish system*, which uses parabolic curved mirrors in the shape of a dish. The mirrors focus the sun's rays onto a receiver mounted above the dish at its focal point. The solar energy heats fluid circulating through the receiver. A small engine mounted at the focal point of the dish generates the electric power. A typical dish achieves temperatures up to 3000 °C and generates about 50 kW of electric power. Like trough systems, dishes can be grouped together to produce more power.

Some experimental dish systems can concentrate the sun up to 60000 times. Because of the unique nature of highly concentrated sunlight to initiate photochemical reactions (photolysis) with certain chemicals and materials, dish systems hold the promise of many applications beyond that of generating electricity: destroying toxic wastes, making chemicals, producing transportation fuels, and creating exotic alloys and ceramics.

This is the least mature of the solar thermal technologies, and before any of the applications can become a commercial reality, much remains to be done on the concentrators and especially on the receiver/reactor subsystems.

Central receiver systems, which have the potential for generating large amounts of electricity, appear to be specially facile for electrical utilities. These systems use mirrors that track the sun and reflect it onto a central receiver atop a tower. The sun heats a fluid in the receiver to 650 °C and higher. The heated fluid creates steam, which drives a turbine to produce electric power. This concept has been proven by several projects, including a 10-megawatt electric system installed near Barstow, California and at a 1-megawatt system in Almeria, Spain that was designed and built as a cooperative effort among EC nations.

4.2. Status and Goals

Advances made in one decade of research in materials, heliostat designs, receivers, transport systems, and computerized controls, have improved the cost-effectiveness of solar thermal systems. For example, parabolic trough systems now generate electricity for approximately 12c per kilowatt-hour, when used in a cogenerating configuration.

Presently there are no privately funded central receiver systems in the USA, however, electric utilities have studied them extensively and have concluded that, using today's technology, they could build 200-megawatt central receiver systems that would generate electricity for between 8c and 12c per kilowatt-hour.

The solar thermal generation of electricity, however, faces two major problems. First, where these systems would be most feasible in the United States, in the Southwest, there is no market. The utilities there are facing an over-supply situation and presently have no need to invest in new capacity, especially from a new technology. The second problem is cost. To make the solar thermal generation of electricity more competitive, the U.S. program is attempting to reduce the cost of solar thermally generated electricity to 5c per kilowatt-hour. To do this requires technical advances in each of the elements of a solar thermal system – concentrator, receiver, and converter. And it requires the application of materials science, fluid dynamics, and systems engineering. I will discuss a couple of the more important challenges facing the technology.

4.3. Scientific and Technological Challenges

First, we need *inexpensive, durable, efficient concentrators.* As much as 50% of the cost of a solar thermal system is by the concentrator, whether it be heliostat, trough, or dish. We have greatly reduced the cost of concentrators. But to make solar thermal systems competitive, we need to cut the costs by another three- or fourfold.

One of the advances that allowed us to reduce the cost of concentrators was the development of the stretched membrane heliostat. This consists of two thin, metal membranes stretched over both sides of a large-diameter ring. A slight vacuum in the space between the membranes provides a concave, focused shape to the reflective surface.

The stretched-membrane concept is simpler, lighter and cheaper than using mirrors. It also allows us to use a front-surface reflector where the stretched membrane serves as a substrate for a thin, reflective, polymer surface. A front-surface reflector avoids the materials and reflectivity problems inherent in a back-surface reflector.

The polymer films we use for the front-reflective surface presently deteriorate too rapidly and cost too much. We are searching for a film that has good specularity, is easily replaceable, has 90% to 95% optical efficiency, lasts at least five years, and costs less than 50 cents per square meter.

An alternative is to depend upon a back-surface reflector, but to use a dependable, extremely thin «micro-glass» that would have the desirable characteristics of glass but that is also lightweight and flexible.

Second, we need *reliable, inexpensive, efficient receivers for central receiver systems.* The receiver sits atop a tower upon which the sunlight is focused from the heliostat field. One way of collecting this energy is to absorb it with a metal plate or tubes, which transmit the energy to molten salt on the backside of the plate or on the inside of the tubes. The salt is heated and piped away.

This indirect absorption of the solar energy by the transfer fluid is not the most efficient. A more efficient method is to have blackened molten salt flow in thin sheets down a panel and absorb the solar flux directly. This direct absorption receiver would simplify design, improve thermal performance, and reduce costs by as much as 25%.

Before this concept can be demonstrated, we have to resolve: what kind of blackening or doping agents should be used; how to keep the flow of the molten salt laminar, especially under conditions such as a high wind; what working fluid would be most stable and retain its properties; and how to develop a molten salt working fluid that has a melting point lower than 150 °C. Resolution of this last point would allow us to reduce or eliminate the present requirement of heating the components or piping that comes in contact with the molten salt.

Some in the European Community are investigating another receiver: the volumetric air receiver. In this design, the solar flux impinges upon a large volume of air moving through a wire mesh. The air absorbs the energy from the mesh and carries it away.

This idea has the advantages of being potentially less expensive and less complicated than the direct absorption molten salt receiver. However, it will be less efficient and there is the potential for the destruction or melting of the wire mesh. A way to address the latter issue would be to use air with suspended carbon particles that would evaporate upon absorbing the solar flux.

5. Closing Remarks and Outlook

I have presented on overview of some of the scientific and technical issues facing three of the renewable energy technologies for generating electricity. But issues don't just arise from the requirements of the technology, they also arise from the requirements of the utilities, the eventual ultimate user. Utilities would like electricity they generate to meet certain criteria, no matter what technology is used.

Can the emerging renewable technologies I have discussed meet the five basic criteria of electric utilities: short lead times, fuel diversity, high availability, dispatchable, and economical? I think they can. And very briefly I will tell you why.

With respect to *short lead times*, the renewable energy technologies may present the utilities with the best option. The construction period of a renewable energy system is very short, as has been demonstrated in America with large photovoltaic systems and with wind farms. Plus, a plant may be added incrementally, allowing easy upgrading as the technology progresses.

The requirement of *fuel diversity* simply means that the utilities do not want to put «all of their eggs in one basket», i.e., they want a variety of supply resources and generation technologies upon which they can rely. The renewable energy technologies can help meet this need. They can add to the fuel resource base and can be utilized almost anywhere on the globe.

But what about *availability?* In one sense of the word, renewable sources of energy are the most available of all energy sources. There will always be sunshine, and there will always be wind. But in another sense, availability also means reliability, the ability to provide the output according to system specifications. The last decade has seen dramatic improvement in this aspect of renewable energy systems. In fact, for many of the systems we have discussed, incremental refinement is all that is required to meet the demands of this criterion.

Dispatchability, the ability to schedule the output of a system to meet demand, however, is a different question. Presently, the intermittent nature of solar energy makes dispatchability one of the most important barriers facing the renewable energy technologies. Although the increasing maturity of the technologies I have discussed today is slowly reducing this barrier, storage remains a primary issue. Its solution is critical to meeting the criterion of dispatchability.

Finally, in some applications renewable energy systems are already *economical* and cost-effective. With the advances being made and with the advances to come from research, renewable energy systems will one day become economical for utility applications also. However, we must be realistic. The energy economy is changing. Supplies of oil, gas, and coal are plentiful and relatively inexpensive, a situation that is likely to be with us for a couple of decades. Consequently, utility cost goals are more stringent, making it more difficult for renewables to compete in this market in the near future. But if technological advances continue nearly as well as they have over the past decade, renewable energy shall eventually meet even this more stringent criterion. And meeting it will not only help meet the dual demands of energy and economic growth for the IEA nations, but also for the vast majority of nations around the world.