Energy for the City of the Future

World energy consumption is expected to grow from about 400 quads per year to more than 600 quads by 2020, a 50% increase. How to supply and configure the energy economy and infrastructure for such a world is one of the principal challenges facing civilization today. In a Forum column describing the new superconductor magnesium diboride, I hinted at a future society whose energy supply might rely on a symbiosis of nuclear, hydrogen, and superconductivity technologies (*The Industrial Physicist*, October/November 2001, pp. 22–23). SuperCity, a visionary future energy community, expands on this concept. It is based on emerging societal boundaries and constraints that can be addressed by foreseeable advances in energy science and technology. No new discoveries are assumed or needed.

Hydrogen will play a crucial role in SuperCity. Imagine a city that is approximately the size and population (about 600,000) of Seattle with roughly an equal mix of urban, suburban–residential, and light-industrial buildings—one that requires a baseline power supply from electrical and chemical sources of 1,500 MW—envisioned for existence by 2020. Hydrogen is not only a way to store electricity, but it also can function as an alternative to fossil fuels as thermal energy and aid in delivering electricity almost without loss.

Not everyone will agree with my projected World or share my selection of social constraints or my idea of the ideal, but the exercise should spotlight some of the issues and solutions for future analysis by scientists and policymakers.

Assumptions

By 2020, we will live in a world where:

- a high degree of international cooperation exists, especially with regard to weapons of mass destruction, and organized terrorism has been contained. Such a world will be necessary to provide the greatest freedom of choice among energy options with maximum security and sustainable fuel supplies.
- worldwide electricity use has soared. Today's industrialized societies consume about 215 quads per year and the rest of the world around 185 quads. By 2020, the split is expected to be 270 to 330 quads, respectively. (A quad equals 10^{15} Btu, or 3×10^{11} kW•h—enough electricity to power three cities the size of New York for a year.)
- either greenhouse-gas-driven global climate change is a confirmed scientific fact or the world's nations have adopted policies to eliminate its possibility, despite whatever uncertainties may remain.

Society will only accept technology solutions that have:

- the least environmental impact, defined as minimizing or perhaps essentially eliminating pollution of the earth's land, air, and water.
- the most benign and minimal intrusion into the eco-structure possible, defined as preserving, and perhaps increasing, Earth's remaining wilderness and land reserves. I also include visual protection of SuperCity's countryside.
- the highest achievable reliability and security of energy generation, delivery, storage, and end use.

By 2020, I envision much of urban and suburban humanity living in communities modeled on various aspects of SuperCity, with energy efficiency being the common thread in all future technology deployment.

Baseline generation

Baseline power is that which is constantly available to the community. It can range from 70 to almost 100% of maximum demand, depending on importable or alternative sources. What technologies will not qualify under our guidelines as baseline supply? Unless an unanticipated breakthrough occurs in carbon dioxide sequestration, energy production by combustion of fossil fuels—oil, gas, and coal—are off the agenda. Implementing biomass—considered "zero emission" on the 1- to 25-year time scale of a chlorophyll-driven photolytic cycle—would inevitably increase land use beyond that necessary for food production. And, like coal, biomass requires continual harvesting and transport to generation centers. As we shall see, most conventional renewables do not have a place at the table either.

T's Studio

The use of hydropower for energy generation and storage involves extensive violation of the ecosystem. One would, in fact, hope that many existing reservoirs could be returned to their natural state. Wind power requires more than 75 square miles to accommodate our target baseline (at a per wind unit capacity of 1 MW spaced 1,000 ft apart). Anyone who has driven through California's Altamont Pass has observed the obfuscation of the landscape that windmills can create and the adverse implications for migratory birds. Solar farms are equally land-use intensive and esthetically unattractive. Economically accessible geothermal sources are usually found near natural geologic formations better put aside as wilderness or parks.

In terms of energy–power density—and thus, minimizing the ecological footprint, maximizing safety and security, and achieving zero greenhouse-gas emissions—nuclear fission power has no peer. In terms of sustainable fuel supply, depending on the choice of radioactinide cycle and reprocess-

ing technology, there exist 300 to 800 years of reserves.

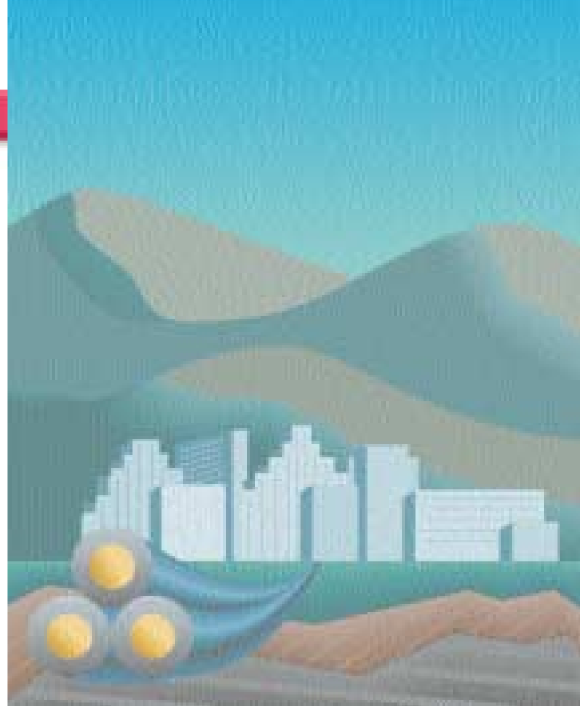
Nuclear-reactor designs based on high-temperature, helium-gas-cooled reactors are now being developed in several countries, notably South Africa, China, Germany, Great Britain, Japan, and Russia, with partial financial support from several U.S. utilities. These reactors use hot (900 °C), high-pressure helium gas derived from passage through the fissile core to drive a turbine connected to an electric generator. Unlike currently employed light water reactors, gas-cooled reactors cannot melt down if the coolant gas is lost. They are designed to dissipate excess heat by passive convection and conduction to their surroundings, and a pyrolytic graphite and silicon carbide shell protects the fuel elements to temperatures of up to 2,000 °C.

The pebble-bed variant of the gas-cooled reactor design, in which baseball-sized spheres of fuel continually flow, has received considerable attention. Spent-fuel pebbles are separated and replaced with fresh fuel in the process, eliminating downtime for refueling. I envision six modular 250-MW (electric) pebble-bed, gas-turbine helium reactors providing an optimal baseline-energy supply for SuperCity and heat for industrial use.

Renewing the nuclear option requires addressing four critical issues—accidents, attacks, disposal, and diversion. First, accidents like those at Chernobyl and Three Mile Island cannot happen with thermally passive, gas-cooled reactors. Also, such reactors do not need massive amounts of water or cooling towers, and they can be placed underground, an essential requirement since September 11, 2001. Most scientists who have studied the problem of high-level waste disposal in depth have concluded there is a vanishingly small risk of leakage and dispersal from carefully chosen repositories on any time scale human beings can intelligently comprehend. Moreover, the volume of waste requiring internment can be vastly reduced through increased deployment of breeding and reprocessing technologies. The last concern—the diversion of reactor fuel and subsidiary materials to producing weapons of mass destruction—is, in my opinion, the most serious remaining obstacle to the widespread return of nuclear power. This is why the boundary condition that world tranquility prevails is vital to the realization of SuperCity. It is absolutely necessary to control and account for every gram of actinide material used for peaceful power production, from tailings to tomb.

Supplemental generation

Baseline generation targets the power supply that must always be available. How much supplemental, or peaking, power an urban area may require depends on many variables, including weather, latitude, diurnal needs, and access to outside sources. Two potential peaking-generation options



are solar roofs and combustion of waste biomass. A large portion of the SuperCity habitat will naturally consist of buildings—industrial, commercial, and residential—whose accumulated roof area lies outside the constraint of minimizing eco-invasion of land for energy production. Assuming SuperCity contains 5,000 buildings with an average roof area of 2,000 ft^2, an installed average dc yield of crystalline silicon of 10 peak W/ft^2 will produce 100 MWe of peaking power at brightest sunlight, or about 7% of baseline. Let's also say that its inhabitants produce an average of 1.5 lb (0.7 kg) of combustible food, paper, and other organic waste daily with an energy density of 10 MJ/kg, or about 40% that of coal. For a population of 600,000, SuperCity can recover a supplemental generation capacity of around 50 MW from a resource that is in accord with both my constraints on greenhouse-gas emissions (net zero in the short term) and restrictions on land use (garbage disposal is necessary).

So by combining solar roofs with communally derived biofuels, we might expect to add a total supplemental power resource of 150 MWe to the electrical baseline. However, there will be times when the sum of the baseline and intermittent supplemental generation is either under or over demand. Clearly, a way to store electricity is needed.

It is often remarked that the Achilles' heel of electric energy is that there are few convenient ways to store it. Electricity is practically the purest form of kinetic energy, but to convert it to potential energy usually means pumping water uphill into storage reservoirs or using batteries.

Of the chemical-storage choices, hydrogen is perhaps optimum because it is readily produced from and returned to electrical kinetic energy. Both paths are necessary because hydrogen must be made from something, and the simplest source is water, H_2O. Under SuperCity's boundary conditions and constraints, hydrogen recovery from biomass or fossil sources is cheating because CO_2 would result by chemical necessity. Present hydrolysis technology is capable of 80% efficiency in converting electricity into hydrogen. I envision transforming the power output of the six modular pebble-bed reactors into hydrogen or direct electricity as needed, with the resulting ancillary oxygen released to the atmosphere or sold for industrial processes.

Energy pipeline

From the date of its discovery in 1911, physicists dreamed of using superconductivity to transmit electricity without loss. However, the current-carrying capacity of the early materials was far below the levels of conventional metallic conductors. By the late 1980s, many Type II superconductors, ranging in temperature operation between the boiling point of liquid helium and above the boiling point of liquid nitrogen, had been discovered that could transport much higher current densities. These developments led to the construction and testing of several superconducting-cable demonstrations that continue today.

Direct current is the preferred method for transmitting electricity through a superconducting cable because ac losses inherent in the physics of Type II materials can cause serious thermal heating and power dissipation. The use of high-temperature superconductors (HTSs) allows a range of possible cooling cryogens, among them liquid and cold gaseous hydrogen. The concept of SuperCity includes a combined electrical–chemical energy transmission–distribution system based on copper oxide or magnesium diboride superconducting wire and liquid hydrogen produced by baseline electricity generation for fuel delivery and as a cryogen. The hydrogen will flow through an underground transmission loop delivering 1,000 MW of electrical power and 200 MWt of hydrogen (700 MBtu/h).

Substations

In the current electric grid, a hierarchy of substations functions to reduce voltage and redistribute power on a local scale. In SuperCity, the function of the substation is expanded and modified to include the storage and generation of hydrogen by reversible fuel cells. To the storage of centrally generated hydrogen and its delivery through the energy pipeline, we add surplus power obtained from SuperCity's solar-roof and waste-biomass sources converted to hydrogen at such substations, which would then regenerate electricity to serve peak-load demands. Redistribution of electricity and hydrogen takes place at lower voltages, down-stepped by solid-state dc transformers over a local network of energy pipelines carrying gaseous hydrogen at 60 to 70 K. Hydrogen would again act as an energy delivery agent and as a cryogen for HTS cables. For security and esthetics, substations would be situated underground.

Perhaps the most unique feature of SuperCity is the consumer's choice between chemical and electric power. For example, cold hydrogen could be passed through heat exchangers to provide air conditioning before undergoing combustion for water heating and cooking. When weather conditions require space heating rather than cooling, the difference between the ambient temperature and that of delivered hydrogen would be thermoelectrically converted to electricity.

Transportation in SuperCity will fully exploit electric–hydrogen concepts. Underground rail transit will be electrically driven, while large surface vehicles will use hydrogen-based fuel cells. Personal vehicles would employ balanced hybrid battery–hydrogen technology. For commuting and local travel, ample battery capacity will sustain short hops between rechargings. For longer travel, fuel cells powered by hydrogen from on-board tanks—initially filled from the household supply and then at fueling stations en route—will get the family to distant destinations.

Energy future

SuperCity is one model of an energy-structured metropolis, from which parts can be drawn for actual application. It is a quiltlike blend of separate, relatively well-understood technologies, although cost–performance challenges remain. The concept should nonetheless prove most useful for gaining some insight into how to stitch these patches together.

Building a SuperCity would be a huge financial and engineering undertaking. Even the independent deployment of its various elements may be beyond the resources of private investment and would likely require government participation. Implementing the technologies represented in SuperCity, collectively or independently, would, I believe, require rethinking present trends in deregulating and restructuring of the electric-energy industry—its re-socialization, if you will—to ensure the timely development and use of advanced technologies in the long-term public interest.

Further reading

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