Radiation Effects and Defects in Solids: Incorporating Plasma Science and Plasma Technology

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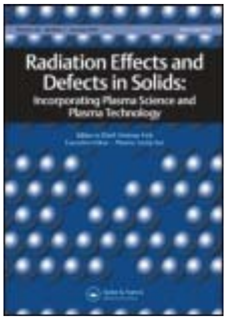

Environment, renewable energy and reduced carbon emissions

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Abstract

Increased energy security and reduced carbon emissions pose significant challenges for science and technology. However, they also create substantial opportunities for innovative research and development. In this review paper, we highlight some of the key opportunities and mention public policies that are needed to enable the efforts and to maximize the probability of their success. Climate is among the uttermost nonlinear behaviors found around us. As recent studies showed the possible effect of cosmic rays on the Earth's climate, we investigate how complex interactions between the planet and its environment can be responsible for climate anomalies.

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Keywords

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- theory,
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Abstract

Jump to section

Increased energy security and reduced carbon emissions pose significant challenges for science and technology. However, they also create substantial opportunities for innovative research and development. In this review paper, we highlight some of the key opportunities and mention public policies that are needed to enable the efforts and to maximize the probability of their success. Climate is among the uttermost nonlinear behaviors found around us. As recent studies showed the possible effect of cosmic rays on the Earth's climate, we investigate how complex interactions between the planet and its environment can be responsible for climate anomalies.

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1. Introduction

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- 1. Introduction
- 2. Fuel cells
- 3. Electrical energy storage
- 4. Solid-state lighting
- 5. Catalysts
- 6. Thermoelectric devices

There are enormous opportunities for achieving greater energy efficiency by replacing inefficient conversion processes with efficient ones. For example, in the transportation sector, gasoline engines that are only 20% efficient might be replaced with fuel cells that are up to 60% efficient coupled to electric motors that are more than 90% efficient. In the case of lighting, incandescent bulbs that are only 5% efficient can be replaced with fluorescent bulbs having an efficiency of 20% today and, when we learn to control the band gap and color of semiconductor lighting, with light-emitting diodes having efficiencies of 50% or more.
Replacing an inefficient conversion process with an efficient one may pose long-term challenges if major barriers stand in the way. Often, the barriers remain resistant to incremental technological advances. In some cases, they can only be surmounted through transformational basic research discoveries that reveal new phenomena or new behavior. In other cases, even if the basic phenomena are understood, long-term applied research may be needed to overcome the barriers.
Two examples of the latter that have relevance for transportation are nanostructured membranes, which can separate small molecules such as carbon dioxide and water based on their molecular conformation, and battery electrodes, which can maintain their optimized nanoscale 'morphology' through millions of ionic charge–discharge cycles. In both cases, we have a good understanding of the basic phenomena, but in neither case is our knowledge sufficient to allow us to apply the scientific principles to specific purposes, such as intelligent tuning of engine operation matched to changing driving conditions.
We highlight key examples of long-term research that is needed to advance the critical technologies for the transportation and building sectors.

2. Fuel cells

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Fuel cells offer the promise of efficient energy use in applications ranging from electricity production for distribution on the grid to transportation in cars and light trucks. The viability of fuel cells is shown by a recent test of fuel cell vehicles that achieved 52–58% efficiency running at 25% power 1**1.** Wipke, K.; Sprik, S.; Thomas, H.; Kurtz, J. *Learning Demonstration Interim Progress Report – Summer 2007*; National Renewable Energy Laboratory Technical Report no. 560–41848, 2007. www.nrel.gov/docs/fy07osti/41848.pdf (accessed January 2008)

View all references. While such efficiencies demonstrate viability, they must be extended to higher power levels to make fuel cells for transportation competitive with internal combustion engines in the commercial market.
The basic fuel cell design is well established by now, much as the basic design of the internal combustion engine was established a century ago. Decreasing the cost of fuel cell production and increasing fuel cell performance and durability represent today's major technological challenges. Electrode materials, catalysts and electrolytic membranes offer the most promising research opportunities for meeting those challenges. We believe that dramatic improvements in these areas are well within reach, if materials science breakthroughs that have occurred through basic research within the last five years serve as any guide 2**2.** Crabtree, G. W. and Dresselhaus, M. S. 2008. *MRS Bull.* , 33(4): 421–428.
[CrossRef], [Web of Science ®]
View all references.
One example of a pertinent advancement pertains to the use of platinum as a catalyst in motor vehicle applications. The catalytic converter in the exhaust system of cars and trucks is well known to motorists. But platinum catalysts are also essential components in fuel cells used by hydrogen vehicles. Until now, platinum's natural scarcity, high demand and consequential high price have posed major barriers to its widespread application as a facilitator of oxygen reduction in fuel cell cathodes. But a recent basic research discovery has shown that adding nickel to the second and third layers beneath the exposed pure platinum surface enhances the catalytic activity 10 times over, thereby significantly reducing the amount of platinum needed in a fuel cell cathode and the consequential cost of the fuel cell 3**3.** Stamenkovic, V. R., Fowler, B., Mun, B. S., Wang, G., Ross, P. N., Lucas, C. A. and Markovic, N. M. 2007. *Science* , 315: 493–497.
[CrossRef], [PubMed], [Web of Science ®]
View all references.

3. Electrical energy storage

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Electrical energy storage in batteries, supercapacitors and other media is central to achieving energy efficiency in electricity production and transportation. The diurnal cycle of electricity demand requires that utility companies vary the production of electricity by as much as 100% within any single 24-hour period. For base load operation, utility companies employ sophisticated combined-cycle plants designed for continuous operation. But to meet peak demand, the companies typically use simple single-cycle gas turbines that minimize capital costs and operate well below the efficiency of the more sophisticated plants. Because they operate for only a few hours a week, some utility companies still use old, coal-fired 'peaker' plants that, by and large, emit significantly greater quantities of carbon dioxide than the base load plants. However, if effective electricity storage existed at the utility scale level, it could bridge the diurnal demand cycle and eliminate or significantly reduce the need for inefficient peaker plants.

Large-scale electrical storage is also required if solar and wind power are to become major contributors to our nation's electricity production. These renewable resources operate on intermittent production cycles, and if they are in widespread use, they will have to be matched to demand with a response time of several minutes or at most a few hours. Unless a large-scale energy storage medium accompanies a large-scale solar or wind generating plant, it will be extremely difficult for the power grid to accommodate the intermittent nature of those plants.

Inefficient fossil-fueled cars can be replaced with efficient all-electric vehicles only when high energy–density batteries become widely available at a reasonable cost. Such batteries do not exist today, and their absence constitutes the primary obstacle to extensive penetration of electric vehicles in the transportation sector. If electric vehicles become prevalent, in principle they could help level the diurnal cycle, since they would mostly be recharged at night. In a sense, they would serve as a natural, large-scale, distributed storage medium for electricity.

The technological challenges for electrical energy storage, like those for fuel cells, lie in electrochemical materials and processes. For example, in the case of the current generation of lithium-ion batteries, the lithium-ion density at the cathode and anode serves as a limitation on the energy density of the battery. And as lithium ions are inserted and extracted at the electrode surfaces during charging and discharging, the electrodes degrade and the cycle lifetime of the battery suffers.

Novel materials provide a wide horizon and rich promise for improving batteries. Consider the case of the lithium-ion battery anode, for example. In this anode, silicon nanowires can store 10 times the energy density of the conventional graphite anode, while still maintaining a delicate surface structure as lithium ions are inserted and extracted 4**4.** Chan, C. K., Peng, H., Liu, G., McIlwrath, K., Zhang, X. F., Huggins, R. A. and Cui, Y. 2008. *Nat. Nanotechnol.* , 3: 31–35.
[CrossRef], [PubMed], [Web of Science ®]
View all references. But achieving similarly dramatic improvements in the performance of the lithium-ion battery system as a whole will require equivalent material advances in the other components. It will also require integration of new technologies that will allow the components to work effectively in partnership. If there is one overwhelming bottleneck for optimizing the energy density of lithium-ion batteries today, it lies in the cathode material. Silicon nanowires might be able to provide a 10-fold improvement over the theoretical limit for materials presently being used 5**5.** Tarascon, J. M. and Armand, M. 2001. *Nature* , 414: 359–367.
[CrossRef], [PubMed], [Web of Science ®], [CSA]
View all references.

In the longer term, developing batteries that transfer two or more charges in the electrochemical reactions at the electrode surfaces represents the greatest challenge and the greatest research opportunity. Success depends on finding a new class of electrode materials with valence greater than one, such as the alkali earth or transition metals. The potential increase in energy density grows with the number of electrons transferred in the basic electrochemical reaction, so that fourfold or greater improvements beyond the best lithium-ion battery technology are conceivable.

Supercapacitors offer an alternative and a complement to batteries for storing electrical energy. In contrast to batteries, which are most efficient when charging or discharging occurs at a slow, constant rate, supercapacitors can store and release electricity very rapidly. In electric cars, batteries are well suited to steady highway driving, but supercapacitors are more compatible to starting, stopping and high-speed acceleration.

Despite rapid progress in the development of supercapacitors in recent years, their stored energy density remains smaller than that provided by batteries. The challenge for supercapacitor research currently lies in the development of high-density charge storage at metal–electrolyte interfaces. Nanostructured interfaces that can store multiple charges at a single site are needed. Recent results indicate that the capacitance of porous interfaces increases 200–300% as the pore size decreases below 1 nm. Further research in understanding and controlling this remarkable nanoscale phenomenon is clearly needed, and it is likely to be very fruitful.

4. Solid-state lighting

Jump to section

Lighting consumes 22% of the electricity we use, and it meets a basic human need that is common to many human activities. The incandescent bulb, the staple of the lighting industry since the time of Thomas Edison, remains a major source of light in industrialized countries, particularly in the residential sector. But as we have already noted, incandescent lamps typically convert only 5% of their energy into visible light. The Federal Energy Independence and Security Act of 2007 requires that by 2012–2014 common light bulbs use 70–80% of the energy used by the present-day incandescent lamps. And by 2020, the act requires that new bulbs use no more than 65% of the energy of the present-day incandescent lamps. Meeting the new standards will require using different technologies. Today's high-efficiency fluorescent lamps, for example, convert 20% of their energy into light and offer a reasonable approach to meeting the 2012–2014 standard. But it seems virtually impossible that fluorescent lamps will improve sufficiently for them to play a dominant role in 2020. Solid-state lighting offers a far more promising approach.

Commercially available solid-state light-emitting semiconductors already rival high-efficiency fluorescent bulbs in reducing energy consumption, and in the future, they promise to offer conversion efficiencies of 50% or more. Solid-state lighting not only provides a path to reduced energy utilization, as required by the 2007 federal law, but the dramatically higher efficiency of light-emitting semiconductors makes them natural partners with solar cells and batteries that can free lighting from the electricity grid in many applications.

Solid-state lighting has already penetrated the commercial market for specialty uses, such as in traffic lights, road signs and architectural lighting. But most of these applications involve colored light. Where white light is needed, semiconductors face significant challenges, both in cost and in technology. Producing white light requires combining colors, and the available phosphors and the available bandgaps currently provided by semiconducting materials limit the nature and quality of the resulting white spectrum. Materials research in doping and defect control of semiconductors and in the development of new efficient phosphors offers fertile ground for science and technology investment 6**6.** Humphreys, C. 2008. *MRS Bull.* , 33(4): 459
[CrossRef], [Web of Science ®]
View all references.

Catalysts exert enormous influence over the speed and selected outcomes of chemical reactions. The biological world provides the most dramatic example of their impact on the efficiency of energy conversion 7**7.** Kraut, D. A., Carroll, K. S. and Herschlag, D. 2003. *Annu. Rev. Biochem.* , 72: 517–571.
[CrossRef], [PubMed], [Web of Science ®], [CSA]
View all references. Catalysts that have taken millions or billions of years to evolve control virtually every biological energy process. They regulate the metabolic pathways of reproduction and growth with minimal energy input.

5. Catalysts

Jump to section

Biological catalysts are enzymes of elaborate structure and functionality, orchestrating every step of the reaction process, from the placement and orientation of reactants to the seamless hand-off of products from one catalytic environment to the next. Human-engineered catalysts, by comparison, are astonishingly simple, typically providing only a fraction of the speed and selectivity of their biological counterparts. At a relatively primitive stage of development for now, they offer an extraordinary opportunity for research to drive them toward the capabilities already demonstrated by biological catalysts.

Catalysts can play a central role in raising energy efficiency 8**8.** Gates, B. C., Huber, G. W., Marshall, C. L., Ross, P. N., Siirola, J. and Wang, Y. 2008. *MRS Bull.* , 33(4): 429–435.
[CrossRef], [Web of Science ®]
View all references. In the transportation sector, for example, hybrid and plug-in hybrid cars would benefit from more selective, faster and more stable electro-catalysts that significantly increase the chemical-to-electrical conversion efficiency in batteries. In the case of hydrogen vehicles, fuel cells currently depend on platinum catalysts to convert chemical energy into electricity. Replacing platinum – which is scarce and expensive – with another material remains a critical technology barrier and a major research challenge.

Although this report treats end-use efficiency, we pause to note that catalysis technology can have a significant import for energy production and distribution. For example, as easy-to-reach resources of conventional oil continue to dwindle, the nearly untapped supply of heavy carbon-rich shale oil or tar sands is likely to assume increasing importance. But extracting and refining these heavy liquid fuels efficiently remain a technological challenge. Developing new catalysts to promote the refining of shale oil and tar sands ultimately will determine whether they can provide petroleum products at reasonable financial and energy costs.

One of the major inefficiencies in our present use of energy is its once-through character. We extract the energy contained in fossil fuels by first converting the fuels into carbon dioxide and water and then exhausting the products into the environment. If we could use the Sun's energy and any excess heat from inefficient energy processes to replace the chemical energy removed by combustion, we could convert the waste products into hydrocarbons and hydrogen for re-use. Developing catalysts that could promote the specific reconstituting reactions poses a major research challenge and opportunity.

Rapid advances in nanoscience and nanotechnology during the past five years have created the potential for converting catalysis from an empirical art into a fundamental science capable of targeting specific reactions and producing materials that promote them. Such a transformational objective is clearly within sight, and it warrants significant increases in the support of fundamental research on nanoscale materials and mechanisms of catalysis.

6. Thermoelectric devices

Jump to section

Our present patterns of energy use are remarkably inefficient. On the way to its end use, more than 55% of the primary energy we generate is lost to waste heat 9**9.** PCAST (President's Council of Advisors on Science and Technology). 2006. *The Energy Imperative. Technology and the Role of Emerging Companies* , www.ostp.gov/PCAST/pcast.html

View all references. Harnessing that heat for productive energy use provides a major opportunity for improving energy efficiency. Thermoelectric devices offer a simple route to capturing waste heat and converting it directly to electricity at its source 10**10.** DiSalvo, F. J. 1999. *Science* , 285: 703–706.
[CrossRef], [PubMed], [Web of Science ®]
View all references 11**11.** Dresselhaus, M. S., Chen, G., Tang, M. Y., Yang, R. G., Lee, H., Wang, D. Z., Ren, Z. F., Fleurial, J. P. and Gogna, P. 2007. *Adv. Mater.* , 19: 1043–1053.
[CrossRef], [Web of Science ®]
View all references.
The thermoelectric conversion process is fairly easy to understand. Electrons moving from hot to cold regions of a semiconductor create an electric current proportional to the thermal gradient – the temperature difference between the two regions divided by the distance between them. Neither moving parts nor chemical reactions are required to generate the electric current, and the thermoelectric conversion takes place within a homogeneous material. The efficiency of a thermoelectric device is characterized by a figure of merit that depends on the temperature at which the device is operating, its electrical conductivity, its thermal conductivity and a parameter known as the Seebeck coefficient, or thermoelectric power. Only a decade ago, the figure of merit of the best thermoelectric devices was about unity, relegating them to niche markets and the research laboratory. But in recent years, rapid advances in nano-composite materials research have raised the figure of merit to 2.5, corresponding to a thermoelectric conversion efficiency of more than 20%, not very different from that of the internal combustion engine.
Thermoelectric devices that either use electricity to produce cooling directly or use waste heat to generate electricity directly have obvious applications in the auto industry. Some of the devices are already penetrating the auto air-conditioning market with electrically driven, seat-mounted coolers producing passenger comfort on hot days and using much less energy than full-compartment air conditioning. Their use for this purpose is expected to increase dramatically during the next five years.
Thermoelectric converters that exploit the waste heat produced by an internal combustion engine can power the increasing number of auxiliary electrical devices used in cars and trucks, such as windows, locks, windshield wipers, lights, GPS navigation systems, video displays and audio for cell phones and digital music sources. If a thermoelectric device could completely replace a vehicle's alternator, it would save 2–10% of the primary chemical energy of the vehicle's fuel.
In hybrid vehicles, thermoelectric devices could have an added advantage. Whenever the internal combustion engine is running, thermoelectric devices could capture a sizeable fraction of the engine's waste heat, convert it into electricity and store the resulting energy in the vehicle's battery. Regenerative braking, which hybrid vehicles currently employ, functions in a similar fashion, capturing up to half of the vehicle's kinetic energy, converting it into electricity and storing the resulting energy in the battery, rather than turning it into heat as is done with conventional breaking.
To achieve a high figure of merit, the current generation of thermoelectric materials use multilayer geometries that scatter ‘phonons’ and thereby lower the thermal conductivity of the device, but they do not scatter the electrons that carry the converted thermal energy as a current 12**12.** Harman, T. C., Taylor, P. J., Walsh, M. P. and LaForge, B. E. 2002. *Science* , 297: 2229–2232.
[CrossRef], [PubMed], [Web of Science ®]
View all references. High-performance multilayer materials are presently made only from deposited films that are not sufficiently robust or available in sufficiently large quantities for the necessary applications.
For thermoelectric devices to be deployed broadly, either bulk materials that possess the same properties as the multilayer materials and can be produced in larger quantities and at lower costs must be found or other approaches must be found to raise the figure of merit. Nanoscale compositional doping as a means of introducing peaks in the ‘density of states’ of the material is one possible approach 11**11.** Dresselhaus, M. S., Chen, G., Tang, M. Y., Yang, R. G., Lee, H., Wang, D. Z., Ren, Z. F., Fleurial, J. P. and Gogna, P. 2007. *Adv. Mater.* , 19: 1043–1053.
[CrossRef], [Web of Science ®]
View all references.
We believe that investing in research to advance the application of nanoscale phenomena in bulk materials for thermoelectric devices has a high potential to recover much of the energy we now lose to waste heat.

7. Lightweight materials

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Lightweight materials present a major opportunity for reducing the amount of energy used in transportation, as we have already pointed out. By most estimates, lowering the weight of a vehicle by 40% will increase its energy efficiency by 25%. Such weight reductions are well within the technical reach of materials now known in the laboratory or used in specialty applications. For example, replacing steel with aluminum can reduce a vehicle's weight by 40–60%. Magnesium is even better, offering a 60–75% reduction, and graphite fiber-reinforced polymer composites offer a 50–60% reduction 13**13.** Carpenter, J. A. Jr., Gibbs, J., Pesaran, A. A., Marlino, L. D. and Kelly, K. 2008. *MRS Bull.* , 33(4): 439–444.
[CrossRef], [Web of Science ®]
View all references.
The barrier to such replacements is simply the price tag. Using the present technology to manufacture components with such lightweight materials, in fact, can increase the costs of the parts by 50–200% compared with using today's standard materials. Reducing the costs must be a major objective of any science and technology program, and it will be difficult to achieve this with 'single-phase' materials, such as aluminum, magnesium and titanium, whose properties and production routes are well known and capped by the limited variability of their compositions and structures. Therefore, we believe that the greatest long-term basic research and long-term applied research opportunities for lightweight materials lie in composites and nanostructured materials with tailored properties 14**14.** Tjong, S. C. and Ma, Z. Y. 2000. *Mater. Sci. Eng.* , 29: 49–113.
[CrossRef]
View all references 15**15.** Wang, Y., Chen, M., Zhou, F. and Ma, E. 2002. *Nature* , 419: 912–915.
[CrossRef], [PubMed], [Web of Science ®]
View all references.
Composites are still in their infancy and comprise a wide range of potential material constituents, morphologies, compositions and internal structures. Additionally, composites can exhibit properties that are normally contradictory, such as high strength and flexibility, optical transparency and electrical conductivity, or high ductility and stiffness. With so many variables in play, there are many possibilities for low-cost manufacturing and new, desirable properties.
The carbon nanotube provides one example of the wide array of opportunities for lightweight new materials. This simple material has a tensile strength of 65 GPa, approximately 100 times greater than that of steel, combined with a density one-fifth to one-sixth lower than that of steel. The carbon nanotube demonstrates but one instance of the combination of properties that can be accessed with new materials. We believe that the innovation opportunities are immense and that applied research into new lightweight composite and nanostructured materials with tailored properties has a very high potential to improve energy efficiency in transportation.

8. Advanced windows

Jump to section

Developing more efficient windows with higher insulation values and selective control of the solar spectrum has been the goal of considerable research in recent years. It is now possible to construct windows that exhibit a net energy gain during the winter if they are properly oriented. Such windows allow the solar energy entering a room to exceed the heat energy that leaves it.
But additional research is needed to make high-performance windows affordable for retrofit applications, especially in the case of residential buildings. Using nanotechnology to produce transparent high-*R*-value panels offers one possible path forward.
Future window systems and active façades have the potential to achieve net energy gains during the winter and substantially reduce air-conditioning loads in the summer. They would adjust daylight, solar gains and ventilation in response to detailed monitoring of interior conditions. In the case of commercial structures, innovative materials and mirrored systems offer the possibility of distributing daylight much deeper into the building interiors, with projected reductions of 50% in average lighting energy usage.

9. Advanced ventilation

Jump to section

Natural-ventilation systems can reduce the seasonal cooling energy requirements by 50% or more in many US climates, while improving human comfort and satisfaction, according to research findings. But natural ventilation requires a façade that has controllable apertures and an interior design that ensures adequate airflow throughout the structure. For a mixed-mode building, this is not an easy undertaking.

Ensuring sufficient airflow for all interior spaces while meeting indoor air quality and fire code standards requires a detailed understanding of fluid dynamics, turbulent flow and thermal behavior in a large multiconnected space under a variety of heat loads and wind conditions. But finding a complete solution to the equations governing turbulent flow in a large, complex building is a daunting task, and simple computational models may introduce unacceptable errors.

There is a serious need to develop straightforward, mixed-mode, natural-ventilation design tools for building architects and engineers. There is also a need to develop effective ways to control natural-ventilation systems under a wide range of conditions.

The influence of indoor air quality on health and productivity is an important issue that is now receiving significant public scrutiny. Further research is needed to identify pollutants, the sources of the pollutants, the limits on acceptable concentration levels and whole-building control measures for volatile organic compounds, mold and other asthma triggers.

10. Ultrathin insulators

Jump to section

Insulating materials in common use today are limited in their effectiveness due to the heat-transfer characteristics of the gases contained in their interiors. As a result, the exterior walls of buildings and the walls of refrigerators must be relatively thick to achieve high levels of insulation.

Aerogels represent the first advance in developing materials that utilize submicron-sized pores to limit the heat transfer through gas molecules in their interiors.

Nanopore materials hold the promise of reducing both thermal radiation and conduction energy transfer. They offer the possibility of developing thin, rigid, high-*R*-value insulation panels suitable for retrofitting the interior surfaces of exterior walls in existing homes without requiring a major renovation of the interior geometry. They could also find applications in appliances such as refrigerators and ovens.

Current windows have far lower insulation levels than the adjacent walls. Oriented nanostructures hold the possibility for developing transparent panels that substantially increase insulation levels while maintaining sufficient clarity for window applications.

In the high-performance thermal insulation materials currently in use, heat transfer by means of radiation plays an important role. For example, at room temperature, infrared radiation accounts for one-third to one-half of the total heat transfer in foam and fiberglass insulation. Tailored nanoparticles added to such insulation could act as reflectors of infrared radiation, substantially reducing the radiative heat loss and increasing the *R*-value of the material by as much as 100%.

11. Thermodynamic cycles

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Heating represents the largest single energy use in residential buildings, and burning fossil fuels for low-temperature applications is a very inefficient use of the commodity from the standpoint of thermodynamics. Combining heat and power systems at the single building or community level can provide substantial energy savings. Heat pumps can also provide greater efficiency.

But today, heat pumps have a coefficient of performance – the ratio of thermal energy delivered to electrical energy consumed – of only 2.5–3. By contrast, the ideal reversible heat pump, a ‘Carnot cycle’, has a coefficient performance of 14 for the same limits between ambient and interior

temperatures. The large efficiency losses in existing heat pumps are caused, in part, by the sizeable temperature differences that occur across the heat-transfer surfaces in the evaporators and condensers. Improving the heat exchangers is a major research challenge.
Techniques currently being explored for cooling integrated circuits in computers offer a possible approach to the problem. In the case of integrated circuits, surfaces with microgrooves have displayed a 10-fold improvement over conventional heat-transfer devices. Other techniques include boundary layer enhancement, such as that used in improved cooling of interiors of gas turbine blades; nanotechnology applications, such as those considered for improving thermal conductivity of thermal fins; and nanofluids, such as those envisioned for enhancing overall convective heat transfer.
Considerable work, especially in Europe, has identified ways to reduce building energy used in cold climates. But finding ways to accomplish this in warm and humid climates is a more challenging problem. As the population continues to increase in such regions, the need for a solution grows.
Finally, the amount of energy consumed in cooling large computer server facilities – now equal to the energy used by the computers themselves – is a mounting problem. The development of a novel system integration of heat pumps and air conditioners within the computer facility could generate considerable energy savings. For example, systems using liquid-cooled radiant panels along with intelligent controls and variable speed compressors could reduce overall energy requirements for air conditioning by one-third or more. The development of dehumidification technologies would also be extremely beneficial.

12. Conclusions

Jump to section

Consumers, companies and governments frequently use criteria other than energy efficiency in arriving at decisions and formulating policies involving energy. Often cost or convenience is the driving factor, with energy efficiency relegated to a lower priority. A survey conducted in 2007, at a time when gas prices already exceeded $a3 per gallon, showed that new car buyers still ranked energy efficiency 16th in priority, well below leading factors such as reliability, safety and purchase price 16**16.** German, J. 2007. *Quoting Strategic Vision, 2007 New Vehicle Experience Study* , USA: American Honda Motor Co.

View all references. With gasoline costing more than $a4 per gallon today, consumer sentiment has changed.
The efficiency of energy usage ultimately depends on the judgments that millions of corporate, government and citizen decision-makers reach in their daily activities, in their homes and on their jobs. Improving end-use energy efficiency requires an understanding of how people arrive at their judgments. Therefore, we believe that social research into human behavior and decision-making must be a high priority.
Although a wide array of factors clearly influence how people reach their decisions involving energy usage, the availability of information is surely one of them. But understanding how the information is best presented, how the consequences of personal and public decisions are best explained and how people are likely to process the knowledge they acquire is essential to the success of any attempt to improve end-use energy efficiency.
Behavioral research into the way energy decisions are made, implemented and accepted, including economic, cultural and psychological factors that affect priority setting, would contribute significantly to designing incentives for increased energy efficiency, facilitating the performance of markets and arriving at regulatory practices where they are needed.

Acknowledgements

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References

- **1.** Wipke, K.; Sprik, S.; Thomas, H.; Kurtz, J. *Learning Demonstration Interim Progress Report – Summer 2007*; National Renewable Energy Laboratory Technical Report no. 560–41848, 2007. www.nrel.gov/docs/fy07osti/41848.pdf (accessed January 2008)
- **2.** Crabtree, G. W. and Dresselhaus, M. S. 2008. *MRS Bull.*, 33(4): 421–428. [CrossRef], [Web of Science ®]
- **3.** Stamenkovic, V. R., Fowler, B., Mun, B. S., Wang, G., Ross, P. N., Lucas, C. A. and Markovic, N. M. 2007. *Science*, 315: 493–497. [CrossRef], [PubMed], [Web of Science ®]
- **4.** Chan, C. K., Peng, H., Liu, G., McIlwrath, K., Zhang, X. F., Huggins, R. A. and Cui, Y. 2008. *Nat. Nanotechnol.*, 3: 31–35. [CrossRef], [PubMed], [Web of Science ®]
- **5.** Tarascon, J. M. and Armand, M. 2001. *Nature*, 414: 359–367. [CrossRef], [PubMed], [Web of Science ®], [CSA]
- **6.** Humphreys, C. 2008. *MRS Bull.*, 33(4): 459 [CrossRef], [Web of Science ®]
- **7.** Kraut, D. A., Carroll, K. S. and Herschlag, D. 2003. *Annu. Rev. Biochem.*, 72: 517–571. [CrossRef], [PubMed], [Web of Science ®], [CSA]
- **8.** Gates, B. C., Huber, G. W., Marshall, C. L., Ross, P. N., Siirola, J. and Wang, Y. 2008. *MRS Bull.*, 33(4): 429–435. [CrossRef], [Web of Science ®]
- **9.** PCAST (President's Council of Advisors on Science and Technology). 2006. *The Energy Imperative. Technology and the Role of Emerging Companies*, www.ostp.gov/PCAST/pcast.html
- **10.** DiSalvo, F. J. 1999. *Science*, 285: 703–706. [CrossRef], [PubMed], [Web of Science ®]

- **11.** Dresselhaus, M. S., Chen, G., Tang, M. Y., Yang, R. G., Lee, H., Wang, D. Z., Ren, Z. F., Fleurial, J. P. and Gogna, P. 2007. *Adv. Mater.*, 19: 1043–1053. [CrossRef], [Web of Science ®]
- **12.** Harman, T. C., Taylor, P. J., Walsh, M. P. and LaForge, B. E. 2002. *Science*, 297: 2229–2232. [CrossRef], [PubMed], [Web of Science ®]
- **13.** Carpenter, J. A. Jr., Gibbs, J., Pesaran, A. A., Marlino, L. D. and Kelly, K. 2008. *MRS Bull.*, 33(4): 439–444. [CrossRef], [Web of Science ®]
- **14.** Tjong, S. C. and Ma, Z. Y. 2000. *Mater. Sci. Eng.*, 29: 49–113. [CrossRef]
- **15.** Wang, Y., Chen, M., Zhou, F. and Ma, E. 2002. *Nature*, 419: 912–915. [CrossRef], [PubMed], [Web of Science ®]
- **16.** German, J. 2007. *Quoting Strategic Vision, 2007 New Vehicle Experience Study*, USA: American Honda Motor Co.