Loucas G. CHRISTOPHOROU*

MATERIALS FOR ENERGY APPLICATIONS

Abstract: Sustainable sources of energy are a prerequisite of a sustainable civilization. And sustainable energy has two basic components: (1) the existence of economically affordable and practically renewable energy sources, which extend far into the future and are compatible with the environment, and (2) energy conservation and efficient use of energy. The energy problem is thus a problem of *energy production and use*. In both of these areas relevant research and technology are of utmost importance.

In this talk I shall stress the importance of materials: (1) in the production of energy and its transformation into useful forms, and (2) in the use of energy. With regard to the production and transformation of energy, I shall stress the importance of materials in the production of more efficient sources of visible light, the more efficient transformation of solar radiation into electrical energy and into useful thermal energy, in energy storage, and in the more efficient transmission of electrical energy. With regard to the uses of energy, I shall stress the possibilities of saving large amounts of energy via energy conservation and increased efficiency of electrical and electronic appliances by using new improved materials.

BASIC ELEMENTS AND FACTS OF THE ENERGY PROBLEM

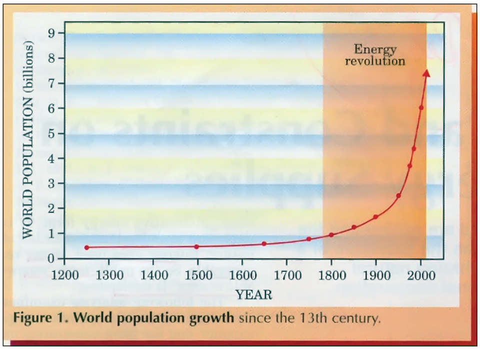
Let me first mention a couple of points about energy:

– Society today consumes huge quantities of energy, which continuously increase, foremost those of electrical energy. Electrical energy is generated principally by the burning of fossil fuels, especially coal, which pollute the environment and produce greenhouse gases. It is estimated [1, 2] that energy production and use is responsible for over 60% of the global greenhouse gas emissions.

– The increase in the demand for energy and the increase in world population deplete the reserves of fossil fuels. The lifespan of oil seems to be especially short (1930–2030) (Fig. 1).

– *Sustainable civilization requires sustainable energy sources.* And sustainable energy has two basic components: (1) the existence of economically affordable and practically renewable energy sources, which extend far into the future and are

* Prof. Loucas G. Christophorou, Academy of Athens



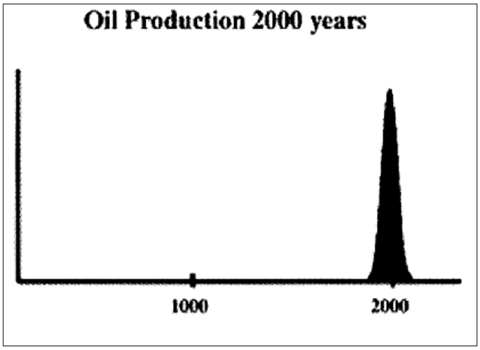


Figure 1. *Left:* The precipitous increase in world population as a result of increased energy consumption.[3] *Right:* Production of oil in two thousand years.[4]

compatible with the environment, and (2) energy conservation and efficient use of energy.

– *The energy problem is, therefore, a problem of* ***energy production and use***. In both of these areas relevant research and technology are of utmost importance. This talk deals with the science, technology, and use of materials for energy applications.

THE IMPORTANCE OF MATERIALS IN THE PRODUCTION AND TRANSFORMATION OF ENERGY

Physical science teaches that to get a particular form of energy from a system, we have to spend, at least as much energy as that which we get. We pay for the particular form of energy we get from a system with another form of energy. For every transformation of energy, is needed energy.

The use of suitable materials for the more efficient transformation of energy into useful forms is paramount.

Let us then look at a few specific examples.

Example 1: Materials for a more efficient production of visible light

It is estimated,[5] that about 25% of the total primary energy consumed annually world wide is due to lighting. It is thus imperative to improve the sources of visible light. Proper materials and new technology (Fig. 2), have allowed and are allowing substantial improvement in the efficiency of light sources, especially in the case of Light-Emitting Diodes (LED). While for incandescent lamps only 4–5% of the consumed energy is transformed into visible light, the efficiency of LED reaches 50–80%.

The basic understanding of the mechanisms via which electrical energy is transformed into visible photons in various materials (organic and inorganic), but also of the properties of the other materials that are used in various types of lamps will allow light sources of higher efficiency.

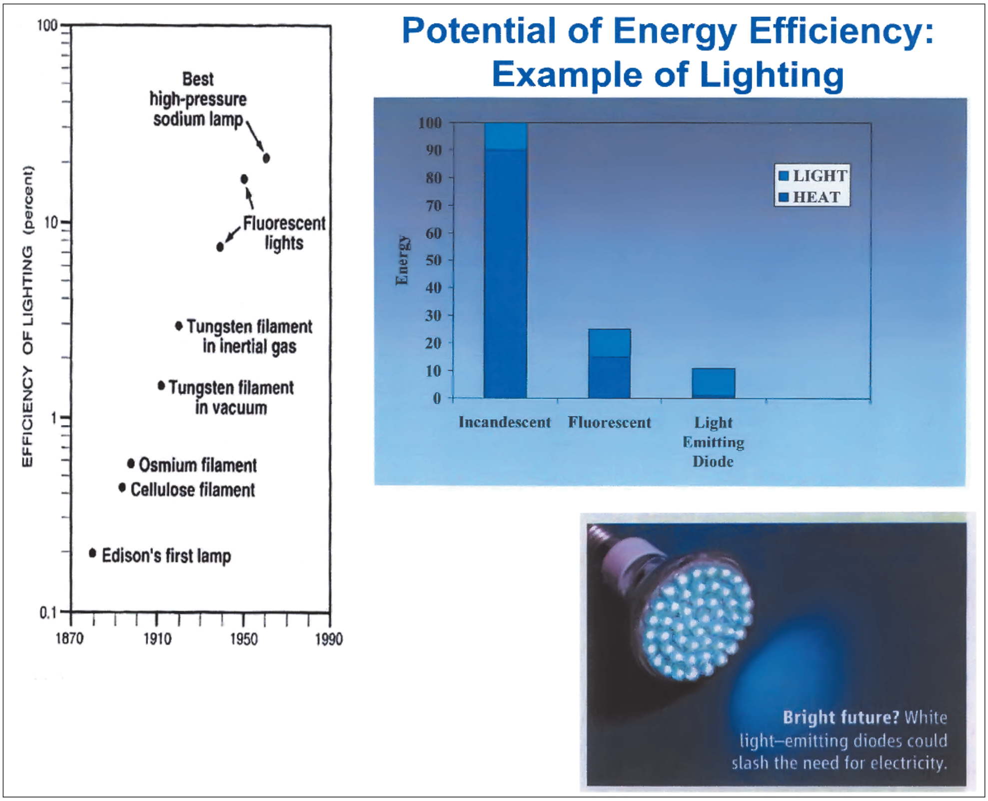


Figure 2. *Left:* Increase in the efficiency of light sources – historical evolution over the last 100 years[6] (Today the best light sources transform electrical energy into visible light 100 times more efficiently than the Edison first lamp 100 years ago). *Right (top):* Comparison of the efficiencies of incandescent, fluorescent, and LED light sources.[7] *Right (bottom):* White-light emitting diode.[8]

Example 2: Materials for the more efficient transformation of solar radiation into electrical energy

Solar thermal systems transform solar radiation into useful forms of energy and fall into two categories: (1) those where solar radiation is transformed into thermal energy and is used as thermal energy, and (2) those where solar radiation is transformed into electrical and is used as electrical energy. In the second category, solar radiation is either transformed directly into electrical as in the case of photovoltaic cells, or it is first transformed into thermal energy and then into electricity using power plants or engines. In all these cases the role of materials is perhaps the most crucial factor.

Let us focus on photovoltaic cells. The direct transformation of solar radiation into electrical energy by making use of photovoltaic (PV) cells is characterized by three stages: (1) the absorption of solar radiation by a suitable material (for instance

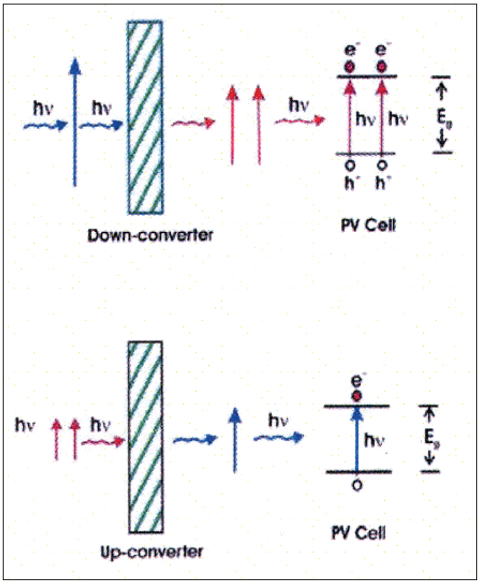


Figure 3. Possible ways to transform the energies of solar photons to enhance the efficiency of electrical energy production.[9]

a semiconductor) of the PV cell and the production of separate electron-hole pairs, (2) the separation of the charges of the pair and the transport of the electrons and the holes (positive ions) to the respective electrodes creating a current in the external circuit, and, for our purpose here, (3) storage of the produced electrical energy.

The role of materials in all three stages is crucial for achieving higher energy conversion efficiencies and lowering the cost of PV cells.

With regard to the absorption of solar photons and the transformation of their energy into electrons, the maximum possible efficiency for single-band gap semiconductors is 31%. In practice, the best energy efficiencies are between 15-20%, while for the commonly used PV cells the efficiencies are about 10%.

Efficiencies higher than 31% are possible if, for example, materials are found which absorb a larger part of the spectrum of solar radiation for the production of electricity[9] (Fig. 3). In this case, suitable materials (converters) could transform photons whose energy $h\nu$ is at least twice the energy gap E_g of the semiconductor ($h\nu \geq 2\,E_g$) into two photons which subsequently are both absorbed, each producing an electron (upper portion of the figure). Similarly, in the case of solar photons with energy less than the energy gap E_g, suitable materials could transform the energy of two such photons into one single

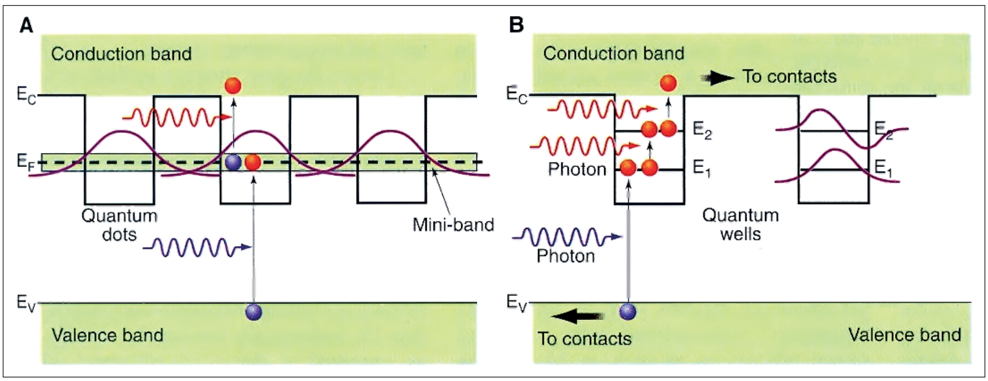


Figure 4. Possibilities of increased efficiency in the production of electrical energy from solar radiation using materials with „mini-bands" or „intermediate bands")[9, 10]

photon with energy higher than the energy gap E_g, ($2\ hv_1 = hv > E_g$), which could be absorbed and produce electrons (lower part of Fig. 3).

It could also be possible to achieve absorption of a larger portion of the solar spectrum by using materials with more than one band gaps, as is shown schematically[9, 10] in Fig. 4. In such materials, „mini-bands", or „intermediate bands" could made possible the absorption of solar photons over a wider energy range, and consequently increase in electricity production. The use of such materials in PV cells could thus increase their efficiency.

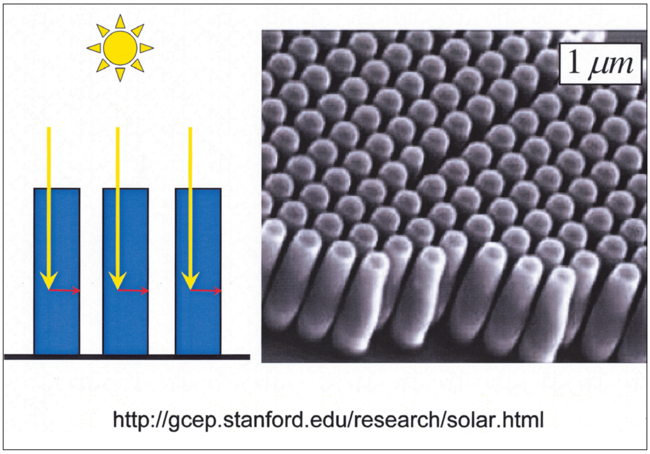


Figure 5. Nano-materials, NANORODS.[11]

Other kinds of materials are also searched for possible use in PV cells, such as low cost organic polymers and nano-materials. Figure 5 refers to NANORODS, [9, 10, 11] where sunlight is absorbed along the length of the rods and the produced charges are transported perpendicular to the nanorods, increasing their efficiency.

Unquestionably, new materials and new technology will increase the efficiency and reduce the cost of production of PV cells, allowing this way, wider use of electricity production from solar radiation. Today, the cost of producing electricity with PV cells is much higher compared to that from other primary energy sources (Table 1).[12]

Table 1. Cost (Euro/MWh, 2005).

Cost	Price*
Natural gas	35-70
Oil	70-80
Coal	30-50**
Uranium	40-45
Biomass	25-85
Wind	35-175***
Photovoltaic	140-450

* Depending on the technology employed.
** This number may increase substantially if the indirect costs of the negative impact of the combustion products (particulates, CO_2, NO_x) on heath and the environment are taken into consideration.
*** Depending on the technology and the location (on shore/off shore).

It should be mentioned that when solar radiation is first transformed into thermal energy and subsequently into electrical energy, materials play a key role in both transformation steps, and since high temperatures are involved in both steps, high temperature materials are of essence (see below).

An interesting area, as well, is the transformation of the infrared (IR) part of solar radiation, or of waste heat (e. g., from internal combustion engines or „waste heat" from factories) into electrical energy using thermoelectric materials.[13]

Example 3: Materials for the efficient transformation of solar radiation into useful heat

In the production of useful heat directly from solar energy, the importance of materials – especially materials with suitable thermal, chemical and optical properties – is crucial. In solar thermal technologies in particular, the challenge is to find suitable materials which make possible and economically feasible the transformation of solar radiation into heat, which is stored as heat and is subsequently extracted, transported and used for generation of electrical energy. Storing energy as heat (thermal storage) is much cheaper and more efficient than storing electrical energy (in batteries).

Of special interest are materials for use in concentrated solar collectors, and fluids of high thermal capacities, such as molten salts, for use in Concentrated Solar Power (CSP) systems, where high operating temperatures (>600 °C) make the storing and transformation of heat into electricity more efficient.

Additionally, organic and inorganic Phase-Change Materials offer possibilities for storing large quantities of heat and recovering it over long time periods later[14] to generate electricity.

Example 4: Materials for energy storage

Storage and recovery of energy using efficient and economically feasible ways, constitutes a crucial element of sustainable development. Figure 6 shows various mechanisms of energy storage and recovery.[15]

It is emphasized that storage of electrical and thermal energy during times of low demand and low cost, as well as the efficient and large-scale storage of electrical energy from wind and solar sources where the energy has to be stored for future use, when generation is interrupted, is very significant. It is also stressed that storing electrical energy from renewable energy sources is necessary to stabilized the power of the transmission grid, which limits the percentage of electrical energy which can be added to the grid from renewable energy sources to less than ~ 15%. Renewable energy sources are not only intermittent for long periods of time, but they are also influenced by weather conditions of short duration (e. g. storms), which reduce the quality of the electric power.

The basic properties of materials and the methods of storing and retrieving energy cover a wide spectrum of basic and applied research and technology, extend

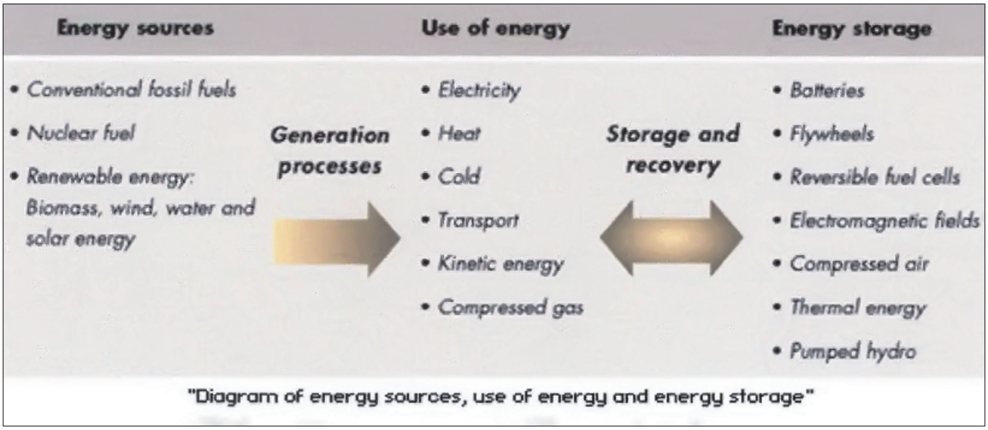


Figure 6. Various mechanisms of energy storage and recovery.[15]

into all states of matter, and in many cases (e. g. batteries) involve reactions between the various states of matter.

Materials which are used to store electrical energy must have high energy density (Wh/kg) and high power density (W/kg). Materials used in small- and large-size batteries must have a low cost, be safe, have small weight and volume and be environmentally friendly, and the batteries themselves must have a large lifetime. In Fig. 7 are shown various systems for storing and recovering electrical energy: in Fig. 7a the power density is given as a function of energy density, and in Fig. 7b the energy per unit volume is given as a function of the energy per unit of weight (size vs weight). It can be seen that lithium-based batteries store more energy per unit volume or weight.[16, 17]

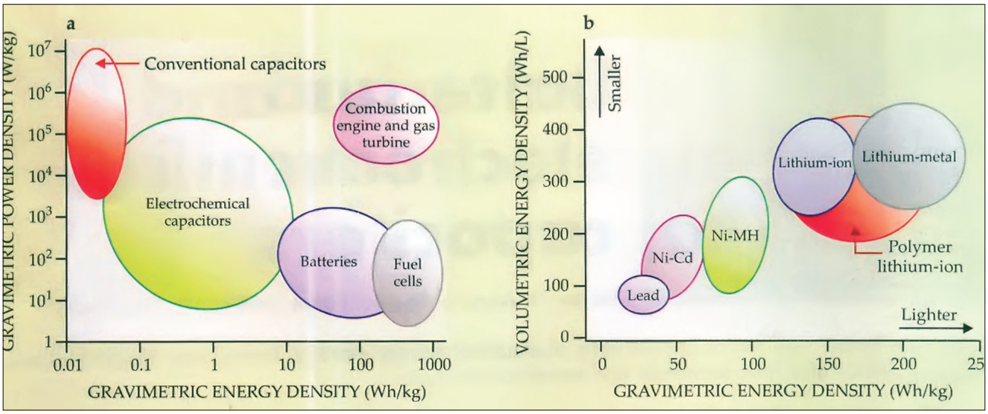


Figure 7. Various systems for storing and recovering electrical energy.
Fig. 7a. Power density as a function of energy density; *Fig. 7b.* Energy per unit volume as a function of energy per unit of weight for various types of batteries.[16]

Figure 8 shows the efficiency of various materials/systems to store energy as a function of the their lifetime (charge/discharge cycles).[18, 19]

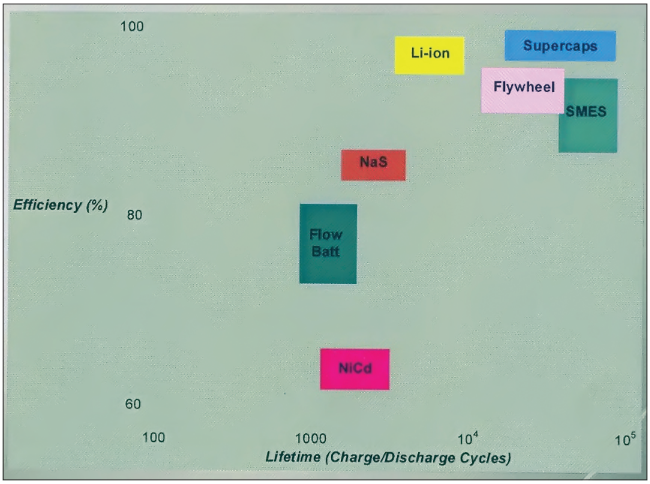


Figure 8: Efficiency of materials/systems for storing energy as a function of their lifetime.[18, 19]

Example 5: Materials for efficient transmission and distribution of electrical energy

Very important is the role of materials in the efficient transmission and distribution of electrical energy, especially in view of the anticipated expansion of the use of electrical energy in the future. Here, there is a need for materials, environmentally-friendly dielectric materials, which allow transmission of electrical power at high voltages to minimize resistive losses, so that energy can be saved especially when the transmission involves long distances. Such may be the case when the production of electricity from renewable energy sources (wind, solar) occurs at long distances from the centers where it is consumed. The same is true for nuclear power plants for electricity generation, which are placed in isolated regions, away from population centers.

Insulating gases (gaseous dielectrics)[20] are especially important in the transmission of electrical energy over large distances, at least until a better technology is found (e. g. superconducting cables) [21]. Today, sulphur hexafluoride, SF_6, is broadly used by industry in equipment for electrical energy transmission and distribution. However, SF_6 is one of the most potent greenhouse gases; its halftime in the environment is ~ 3.200 years and its „Global Warming Potential" is ~ 24.000 high-

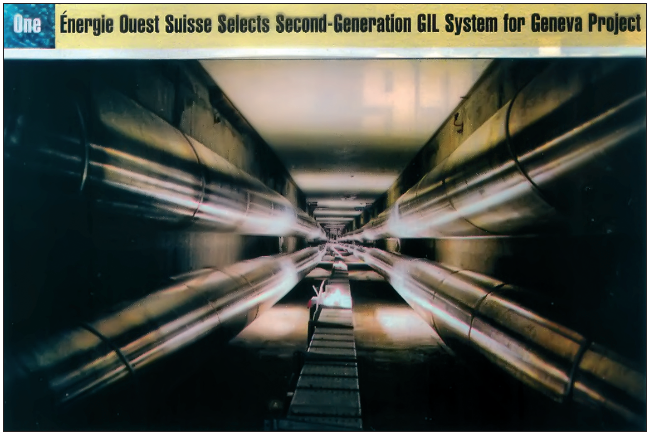


Figure 9. Gas-insulated transmission lines placed in a tunnel and insulated with the dielectric gas mixture 80% N_2 + 20% SF_6.[23, 24]

er than that of CO_2. One molecule of SF_6 is as damaging to the environment in terms of global warming as are 24.000 molecules of CO_2.[22]

Basic and applied research found materials which are not greenhouse gases or which use much smaller quantities of SF_6 for use in electrical energy transmission: High pressure N_2 (~10 atm) or mixtures of N_2 and SF_6 where the concentration of SF_6 is < 15%.[23] Figure 9 shows pipes in a tunnel containing the electricity transmission cables (gas-insulated transmission lines), which are insulated by such gases/mixtures.[20, 23, 24]

With regard to electrical transmission using gas-insulated cables, the dielectric strength of the gas and its long-range stability and inertness, along with its heat transfer properties at temperatures lower than ~110 °C are important gas requirements (see references 23 and 25. See also these references for desirable properties of gases used in gas-insulated circuit breakers, substations and transformers).

THE IMPORTANCE OF MATERIALS IN ENERGY USE

In the countless uses of energy there are many possibilities of increasing efficiency and of saving large and small amounts of energy, which add up to big numbers. Energy conservation constitutes the most important source of energy at our disposal; it also constitutes an important „technology" for reducing greenhouse gases.

Allow me to stress the crucial role of materials in just two areas.

Example 6: Materials and technology for electrical and electronic equipment

Figure 10 shows data[26] (in blue colour) on the consumption of energy by refrigerators in the USA. Since 1974, when the price of primary energy began to increase precipitously and conservation measures began to be put in place, the use of new materials and technology resulted in substantial reduction in the amount of ener-

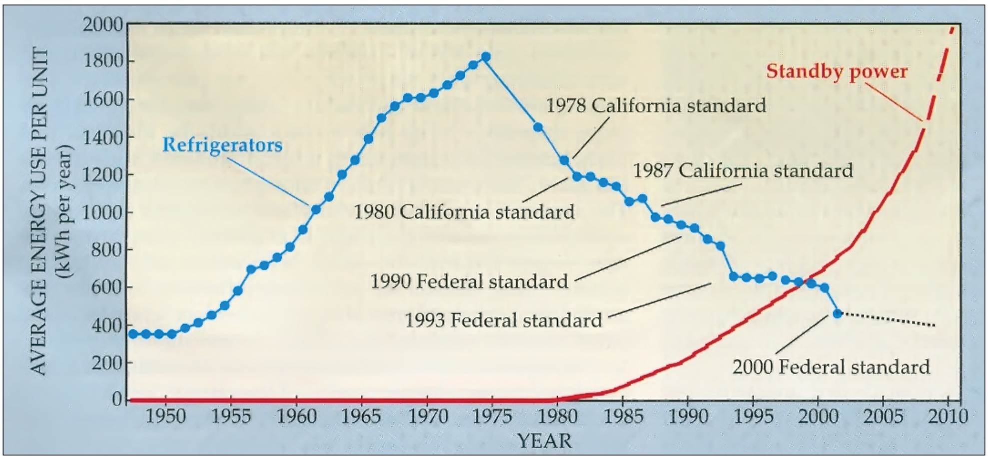


Figure 10. Consumption of electrical energy by refrigerators in the USA (blue color), and standby consumption of electrical energy by electronic equipment.[26]

gy consumed by refrigerators, while the size of the refrigerators increased and their cost reduced by over 60%.

In the same figure, the red line refers to the consumption of electrical energy by electrical and electronic equipment, mainly computers, in a „standby" mode. Electronic equipment even when not in use, but is „on" and „inactive" or „standby", consumes significant amounts of energy.

In Table 2 are given the amounts of electrical energy consumed by representative types of electronic equipment when „on" and „active", „on" but „inactive", and „standby".[2] The laser printer, TV, and computer screens consume large quantities of electrical energy. New materials are needed (such as the Liquid Crystal Displays used in the screens of laptop computers), which consume less energy, considering the huge number of such equipment in use.[27] The data in Table 2 also show how important it is to switch off appliances not in use.

Table 2: Power consumption of various gadgets in watts (40 W is 1 kWh/d).[2]

Gadget	Power consumption (W)		
	„on" and „active"	„on" but „inactive"	„standby"
Computer box	80	55	
Cathode-ray display	110		3
LCD display	34		2
Projector	150		5
Laser printer	**500**	**17**	
Laptop computer	16	9	0.5
TV	100		10

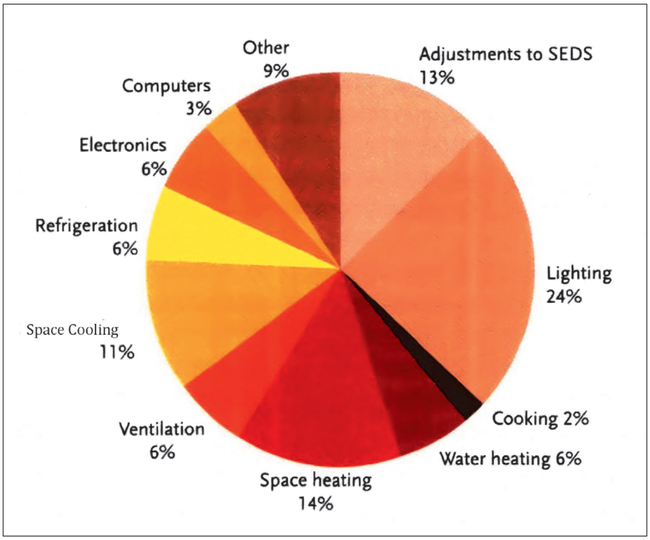


Figure 11. Consumption of energy in commercial buildings in the USA. [5]

Example 7: Materials for buildings

In this area there is a huge potential for energy savings and improved energy efficiency. It is estimated[5] that the supply of energy to buildings constitutes 38% of the total annual world consumption of primary energy (excluding traditional biomass). Large quantities of energy are spent for heating and cooling buildings, hot water, lights, and electrical and electronic equipment.

Figure 11 shows the distribution of energy consumption in commercial buildings in the USA. 5 Although these data are for the USA, they show, nonetheless, that large sums of energy are used for lighting and heating/cooling of buildings.

Large quantities of energy could be saved by using more efficient building technologies, more efficient electrical equipment, new and improved light sources and new methods and mechanisms of space illumination, but also by using appropriate materials and material technologies (see, for instance Refs. 2, 5, 7). From this perspective, the building can be considered an „energy system".

OVERALL IMPROVEMENT IN EFFICIENCY OF ENERGY PRODUCTION AND USE

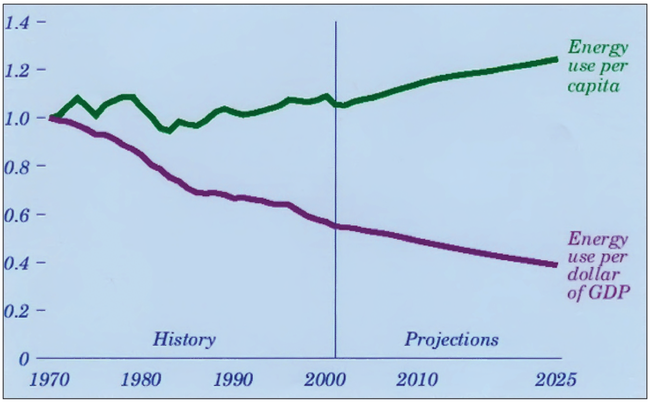


Figure 12. Energy use per capita and energy use per dollar of GDP in the USA, 1970–2025 (1970=1).[27]

The advancements in the materials area indicated, but also in numerous other areas ranging from nuclear power plants to nanotechnologies, contribute substantially to the overall improvement in efficiency of energy production and use. Figure 12 shows that in the USA, measures for energy conservation and improved energy efficiency resulted in a substantial decrease in the amount of energy consumption per dollar of GDP.

Similar data were published for the European Union.[1]

Energy efficiency clearly increases the effectiveness of energy use.

CONCLUSIONS

The energy problems are serious, big, multidimensional, long-lived and common; they demand infrastructure, persistence, and coordinated and long-range planning and investment.

Basic and applied research and technology in the materials area are essential for any country, in order to use effectively new materials and material technologies for more efficient use of energy.

LITERATURE

[1] World Energy Outlook 2008.
[2] D. J. C. MacKay, *Sustainable Energy-without the hot air*, UIT, Cambridge, England, 2009, ISBN 978-0-9544529-3-3.
[3] P. B. Weisz, Physics Today, July 2004, p. 47.
[4] James Leigh, *A geopolitical tsunami: Beyond oil in world civilization clash,* Energy Bulletin, September 2008 (http://www.energybulletin.net/node/46451).
[5] InterAcademy Council Report, *Lighting the way – Toward a sustainable energy future*, October 2007, ISBN 978-90-6984-531-9.
[6] V. Smil, *Energy in World History*, Westview Press, Inc, Boulder, Co, 1994.
[7] See for example, C. J. Humphreys, MRS Bulletin, Vol. 33 (April 2008), p. 459 (www.mrs.org/bulletin) *Energy Future: Think Efficiency*, American Physical Society, September 2008(http://www.aps.org/energyefficiencyreport/);http://lighting.sandia.gov/XlightingoverviewFAQ.htm
[8] R. F. Service, Science 325, 14 August 2009, p. 809.
[9] USA DOE 2005 Basic Energy Science (http://www.sc.doe.gov/bes/reports/abstracts.html#SEU).
[10] N. S. Lewis, Science 315, February 2007, p. 798.
[11] http://gcep.stanford.edu/research/solar.html
[12] See also, Επιτροπή Ενέργειας της Ακαδημίας Αθηνών, *Πυρηνική Ενέργεια και Ενεργειακές Ανάγκες της Ελλάδος*, Αθήνα 2009 (Energy Committee of the Academy of Athens, *Nuclear Energy and the Energy Needs of Greece*, Academy of Athens, Athens, 2009).
[13] See, for instance, D. Chubb, *Fundamentals of Thermophotovoltaic Energy Conversion*, Elsevier 2007, ISBN 9780444527219; *Thermophotovoltaic Principles, Potential, and Problems*, AIP Conf. 404, 1997; T. M. Tritt, H. Böttner, and L. Chen, MRS Bulletin, Volume 33, April 2008, p. 366 (www.mrs,org/bulletin); http://en.wikipedia.org/wiki/Thermophotovoltaic
[14] See, for instance, M. Kenisarin and K. Mahkamov, Science Digest-Renewable and Sustainable Energy Reviews 11, 1913 (2007); http://en.wikipedia.org/wiki/Phase_Change_Material
[15] http: //ec. europa. eu/research/energy/nn/nn_rt/nn_rt_st/article_1154_en. htm
[16] H. D. Abruna, Y. Kiya, and J. C. Henderson, Physics Today, December 2008, p. 43; J. B. Goodenough, H. D. Abruna, and M. V. Buchanan, eds., *Basic Research Needs for Electrical Energy Storage: Report of the Basic Energy Sciences Workshop on Electrical Energy Storage, April 2-4, 2007,* US Department of Energy, Office of Basic Energy Sciences, Washington, DC (July 2007), http://www.sc.doe.gov/BES/reports/files/EES_rpt.pdf
[17] See, also, Basic Research Needs for Electrical Energy Storage, Office of Science, U. S. Department of Energy, www.science.doe.gov/bes/reports/files/EES_rpt.pdf
[18] Peter Hall, in Materials UK- Materials for Energy http://www.matuk.co.uk/energy.htm
[19] See, also, Basic Research Needs for Electrical Energy Storage, Office of Science, U. S. Department of Energy, www.science.doe.gov/bes/reports/files/EES_rpt.pdf και www.ge.com/battery/resources/pdf/ImreGyuk.pdf
[20] L. G. Christophorou, Nuclear Instruments and Methods in Physics Research, Vol. A 268, 1988, p. 424.
[21] J. W. Ekin, in L. G. Christophorou, J. K. Olthoff, and P. Vassiliou (Eds.), *Gaseous Dielectrics X,* Springer, NY, 2004, p. 423.

[22] L. G. Christophorou and R. J. Van Brunt, National Institute of Standards and Technology, Report NISTIR 5685, July 1995; Office of Atmospheric Programs, U. S. Environmental Protection Agency, *Greenhouse Gases and Global Warming Potential Values*, April 2002; http: //www. eia. doe. gov/oiaf/1605/gwp. html
[23] L. G. Christophorou and R. J. Van Brunt, IEEE Trans. Dielectrics and Electrical Insulation Vol. 2, 1995, p. 952. L. G. Christophorou, J. K. Olthoff, and D. S. Green, National Institute of Standards and Technology, NIST Technical Note 1425, November 1997.
[24] J. Riedl and T. Hillers, IEEE Power Engineering Review, September 2000, p. 15, Transmission and Distribution World, January 2001, p. 30.
[25] L. G. Christophorou, „Gaseous Dielectrics in Power Transmission and Distribution”, in DEMSEE (2007, Istanbul), pp 13-19.
[26] L. R. Glicksman, Physics Today, July 2008, p. 35; A. Cho, Science 325, 14 August 2009, p. 807.
[27] http://www.eia.doe.gov/oiaf/archive/aeo03/figure_3.html