STUDY OF ENERGY STORAGE INCLUDING SOURCES, UTILIZATION AND ECONOMICS

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Keith Ellis Robertson

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THESIS
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This is to certify that the

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presented by

Keith Ellis Robertson

has been accepted towards fulfillment
of the requirements for

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Carl W. Hall
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STUDY OF ENERGY STORAGE INCLUDING SOURCES, UTILIZATION AND ECONOMICS

By

KEITH ELLIS ROBERTSON

A THESIS

Submitted to the College of Agriculture of Michigan State University of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

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SUMMARY

The project on energy storage was set up to investigate the possibilities of developing energy storage units for agricultural uses and to provide a broad general basis from which further projects can be developed.

The energy reserves of the world are expected to reach a production peak within the next fifty years. Therefore, the bulk of our energy after 2000 A.D. will have to be supplied by nuclear power plants or by the income sources of energy. Energy storage units will be necessary to obtain full use of the energy produced by nuclear power plants because of their base-load character. To adequately utilize energy from the sun, the major source of income energy, energy storage units will be necessary because of its intermittent nature.

It was found that there are several possible applications where energy storage units can be utilized. Approximately $250 a year could be used to construct and operate individual house-heating energy storage units charged by off-peak electricity. A unit to heat water for home and dairy use by using solar energy would be worth $75 a year. Solar energy could be readily adapted for space heating, although the yearly value of a collector and storage unit

would be approximately $100. Energy storage systems will have to be designed, constructed, and tested to determine whether or not these economical requirements can be met.

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INTRODUCTION

The modern civilization of man and his high standard of living have come about largely because of the vast amounts of useable energy available to him. In building a complex society enormous quantities of energy are being used, much of it never to be regained again. Most of the energy which has been used has been taken from the accumulated capital reserves of the world, the fossil fuels. The rate at which the fossil fuels are being used is continually increasing and with a rapidly increasing world population there is no doubt that they will continue to be used much faster than they are being replaced. Ayres and Scarlott (1952) wrote that of all the fossil fuel recovered since the earth was created two billion years ago, more than 86 per cent has been used since 1900. With more and more energy being used and rising production and conversion costs the price of energy has been steadily rising. If convenient and economical means of storing energy could be devised they would extend the use of the present energy resources and would aid in making much better use of solar energy and energy from nuclear power plants.

Importance of Storing Energy

In the past decade the possibilities of using atomic fission for the production of heat and electricity have become realized. Several plants have been constructed and are now being operated and tested. Others are being planned as more information is obtained in solving the engineering problems. It has been estimated by Brown, et al., (1957) that atomic fission will supply one-third of the total energy consumption by the end of the century and that it will represent a significant proportion of world power production by 1980. If this occurs it will be necessary to store off-peak energy because of the base load character of atomic energy plants.

The sun has been the ultimate source of all energy used by man. The fossil fuels are the result of vegetative growth accumulated thousands of years ago. Since these fuels are being used much faster than they are being stored, it may become necessary or economically desirable in the near future to use the energy from the sun directly. Man has in the past used very small amounts of the sun's direct energy with some applications developed for field drying of crops, water heating, and limited space heating. Because of the low intensity, wide scattering and intermittent nature of solar energy more abundant use has not been made of it although large amounts are being received every day the sun shines. Daniels (1955) writes that the average daily supply of solar energy in much of the world is of the order of 2,000 Btu per square foot. If this energy could be collected and stored for cloudy days and night use we would not need to depend so heavily on our diminishing supplies of fossil fuels.

In discussing bulk power generation Cook (1959) writes:

> "In any discussion of the use of other forms of energy for this purpose, the possible use of solar energy must be considered because of the large amounts of heat which reaches the earth. Here also several developments are needed. One is a vast improvement in energy converters and the other is vastly superior, large-scale energy storage means. Better energy storage means are needed in many other applications, but the present rate of progress does not seem sufficient for our need if solar energy is to be used for generating bulk electric power."

Referring to the American Institute of Electrical Engineers, Suits (1959) says:

> "In our organization we have made a thorough study of the economic and technological aspects of solar energy. Without going into detail, we will summarize by saying that before solar energy can become competitive, we must improve energy-storage techniques by about six times in comparison to best present practice, and must develop solar cells that are 100 times cheaper than anything now available."

The electrical power generation and distribution systems of the world could readily use energy storage systems. The consumer demand for electrical power varies with the time of day and the time of year. The generation and distribution systems are built to supply power for peak demand periods. Therefore, during off-peak periods less efficient use is made of the invested capital and equipment. Plans have been presented to store off-peak energy produced and thereby even out production curves. One method of storage is pumped-water, where water is pumped from a low level reservoir to a high-level reservior during low demand periods. The water is then used to generate energy for peak demand periods. It also might be economical to develop electrical, heat, or some other form of storage units at the individual points of use. In many areas off-peak rates for electricity are one half or less than regular rates. If simple efficient units could be developed and used they would help to even out electrical demand curves.

In the area of electrical energy storage there has been an unaccountable lack of progress. There has been no basic advance in principle for fifty years. Michalis (1959) describes as the "Cinderella" of electrical science the branch which deals with energy storage. He further indicates that a form of storage cell which would enable an electric vehicle to become a serious competitor to the internal combustion engine-powered automobile is needed.

Michalis (1959) and other prominent men in the field agree that it is time that a major program of research in the storage of energy be undertaken.

With rising production costs and declining prices the agricultural producer could well benefit from a decrease in farm energy costs. If by developing simple methods of storing energy new energy sources could be used or energy from conventional sources could be obtained at lower prices, then this development would definitely be advantageous to the agricultural producer.

Objective of Research

Much interest has been shown in the need for methods of storing energy. This project was set up to investigate the work that has been done on energy storage and to provide a broad general basis from which further promising projects can be developed.

REVIEW OF LITERATURE

There are many different methods and forms of storing energy. One of the simplest and most common is the storage of the fossil fuels such as coal, oil, and gas. Although these fuels are easy to store they are often not the most convenient form to transport or use for many purposes. Heat, mechanical power, and electricity can be obtained from the fossil fuels through conversion processes, and these are the forms in which large quantities of energy are transported and utilized. For this reason it may be convenient and desirable to store energy at times as heat, mechanical energy, or electricity.

Storing Energy as Heat

Sensible heat storage

Heat may be stored as sensible heat by raising the temperature of materials having a high specific heat. A report by Battelle Memorial Institute (1958) indicates that approximately 1,600 cubic feet of water would be required to store one million Btu with a 10° F. temperature change. Dry sand would store the same energy with approximately 5,900 cubic feet. There are many other materials which could be used to store heat by the sensible heat method but all of them require large volumes and would involve considerable insulation to keep heat loss at a minimum. Even with these limitations many sensible heat storage units have been designed and a few have been installed and used.

A storage oven heated electrically at night when power demand is low is being widely used for space heating in West Germany, Austria, and Switzerland (Mechanical Engineering, 1959). Heat is stored in blocks of compressed magnesite, chosen for its local availability and favorable materials constants. Mineral-wool insulation and louvres surrounding the unit retain the heat until needed. The temperature of the core varies between 572° F. and 1,292° F. with the surface temperature remaining at 158° F. The louvres which can be automatic or hand operated are the only adjustment for the release of heat.

In a report printed by the United Nations (1957) the storage of energy as the sensible heat of water or pebbles was discussed. Hot water storage is simple and effective if the tank is well insulated. Some heat is lost through heat conduction in the water storage but more is lost through convection by circulation of water within the tank. The report recommends that barriers should be introduced in the water tank to reduce circulation of the water.

Several space heating systems have been designed and installed which use water tanks for storing energy. Yellott (1957) describes one which was installed in Albuquerque, New Mexico. An 890 square foot aluminum collector surface covered with single sheets of window glass is used to collect solar heat. Water is used as the working fluid and heat storage is afforded by a 5,000 gallon tank buried beside the building. The supplemental heating system of the Western Massachusetts Electric Company's new headquarters building is described by Turnbull (1960). During the peak mid-winter heating period, heat in addition to the regular supply is provided by 8,000 gallons of 205° F. water heated by two 195 kilowatt electric heaters during off-peak hours and stored in an insulated tank in the basement. Input to the storage during an eleven hour period can carry the building heating load for thirteen hours. The system will be used to provide operating cost data and to demonstrate feasibility for such a system for large commercial buildings in northern areas.

The solar heated houses designed and put into operation in and around Tokyo by Masanosuke Yanaginacki are described by Yellott (1960). The heat storage for a house built in 1958 is provided by two concrete tanks in the basement. A 9,500 gallon tank stores water heated by the solar collector during the day. A 2,375 gallon tank stores water warmed by a three horsepower heat pump. The warmer water from the small tank is used directly for space heating.

According to a United Nations Report (1957) the most effective and cheapest heat exchanger for a flowing stream of gas or air is a bed of small pebbles one or two inches in diameter or larger. Heat loss in such a storage is very small because of the small area where the pebbles touch the surfaces. Transfer of heat of pebbles to the air is very good because the total surface of the pebbles is larger and the winding path through the pebble bed assures intimate contact of all parts of the air with the pebble surfaces.

McDow (1957) designed and tested a heat storage unit in which heat was stored as the sensible heat of concrete spheres. In an actual model rocks would be used instead. He determined that a four inch diameter rock would provide the maximum amount of heat storage with a minimum pressure drop across the system. Low air mass velocities of 320 pounds per hour per square foot provided the greatest heat transfer and the most economical operation. It was determined that sixty-eight per cent of the heat stored was in the storage unit after three days. His calculations showed that a seven foot cube storage unit with stones could furnish approximately 25,000 Btu per hour for sixteen hours a day. A storage unit using sensible heat should be placed within the building where the heat is being utilized to increase efficiency. It should be cubical or cylindrical in shape so as to enclose a maximum volume with a minimum outside area to insulate.

The heat transfer data for a pebble bed heater using 0.375 inch diameter alumina balls has been obtained by the

N A S A (1960). The bed is heated by burning gasoline and passing the combustion products through it. The bed is used to supply high-temperature air for the experimental evaluation of hypersonic flight problems. Heat transfer coefficients were obtained for a large range of air mass velocities with the pebble bed at a maximum temperature of 3,000° F.

Sporn and Ambrose (1956) conducted tests for the American Gas and Electric Service Corporation using an air source heat pump in connection with a sensible heat storage system for space heating. A high temperature storage system was used in which water was stored during the heating cycle by means of the heat pump so that it could be directly used for space heating. The heat source for the heat pump was a solar collector.

Davis and Lipper (1957) designed and built a space heating system which incorporated a heat pump, solar collector, and a heat storage unit. The storage was designed to supply a 20° F. temperature rise for 24 hours to the air supply for heat pumps of current design. The low (evaporator) side storage consisted of water placed in plastic-film-sealed tin cans four and one-half inches in diameter and seven inches high. Heat was stored or released in latent (at 32° F.) and sensible form by the air enroute to the heat pump. The cans were placed in overlapping rows so that the air made effective contact to provide heat transfer to or from the water. It was found necessary to include an expandable, anti-freeze-filled sleeve along the central axis within the cans and extending above the water surface to prevent can rupture. When the water froze, the anti-freeze expanded in the container above the ice surface. The results of the study revealed that after adding a solar collector and storage unit to the heating system the air temperature increase provided to the heat pump varied between 12 and 23° F. Continuous operation of the two systems during two three-week periods in January and February showed that the coefficient of performance of the supplemented heat pump averaged 17.5 per cent higher than that of the unit using outside air alone as the heat source.

Taylor (1959) describes how the thermonuclear bomb has been developed to the extent that it could be used to produce heat for storage on a large scale. The scientists have learned how to use the nuclear explosive underground and trap the heat such that it could be stored and used gradually. Formulas have been worked out by the Humble Oil and Refining Company indicating that one to ten megaton explosives detonated in salt or limestone could supply heat enough to produce electric power at competitive prices with ordinary steam-electric systems.

Storing heat in chemicals

Much interest has been shown in the use of chemicals for storing heat. There are several phenomena which can be used for heat storage. The heat of fusion is the heat liberated when suitable materials change from a liquid to a solid form. The heat of hydration is the heat generated when certain substances are combined with water. The heat of chemical change is the heat given off when certain chemicals react with each other. The major advantage, and one which is very important in many instances of chemical heat storage systems is the relatively small volume required.

Telkes (1959) developed a solar cooking oven which used the heat of fusion principle for heat storage. It was found that the sensible heat of the aluminum of which the cooker was constructed was not sufficient to bridge over intermittent cloudy periods or extend the cooking period into late afternoon. Heat storage was obtained by using a mixture of sodium sulfate (Na_2SO_4), potassium sulfate (K_2SO_4), calcium sulfate ($CaSO_4$), and lithium sulfate ($LiSO_4$). The relative amounts of these materials determine the transition temperature between 380° F. and 460° F. The heat content in the cooking range, 250° F. to 400° F., is around 120 Btu per pound.

Some other materials which are easily available, sometimes as by-products, according to Telkes (1955) are:

$Na_2SO_4 \cdot 10H_2O$ with a heat of fusion of 104 Btu per pound, $CaCl_2 \cdot 6H_2O$ which has a heat of fusion of 75 Btu per pound, $Na_2CO_3 \cdot 10H_2O$ which has a heat of fusion of 115 Btu per pound, $Na_2HPO_4 \cdot 12H_2O$ which has a heat of fusion of 114 Btu per pound, and $Ca(NO_3)_2 \cdot 4H_2O$ which has a heat of fusion of 90 Btu per pound. The transition temperatures of these compounds range between 84° F. and 108° F.

The heat of fusion of disodium phosphate ($Na_2HPO_4 \cdot 12H_2O$) was used to store heat in a system described by Etherington (1957). The heat storage system consisted of two heat exchangers and a circulating pump. A light mineral oil was circulated through a useage heat exchanger where heat was transferred from tap water to oil and from oil to tap water. The oil then bubbled through a storage heat exchanger in which it absorbed or rejected heat from or to the heat storage salt. Two layers existed in the storage tank with the oil as the top layer and the storage salt as the bottom layer. Oil was pumped from the top layer through the heat exchanger where it was heated or cooled by domestic hot or cold water and discharged through a perforated pipe at the bottom of the salt layer. The oil absorbed or rejected heat as it rose through the storage salt phase. The heat transfer rates were greatly improved over those recorded for systems in which the storage cell was enclosed in sealed containers. The minimum rate of heat transfer for this method in this particular system was about 800 Btu per hour. The excellent heat transfer was due to the high coefficients of heat transfer characteristic of direct contact heat exchange systems. The salt volume was 0.45 cubic feet and the oil volume was 0.43 cubic feet. Based on salt volume alone, the minimum latent heat realized on salt freezing was 4,650 Btu per cubic foot and the maximum was 10,200 Btu per cubic foot.

A report by Battelle Memorial Institute (1958) suggests that the heat of fusion of paraffin waxes might be used for heat storage in the range 100° F. to 130° F.

The utilization of the heat of hydration of calcium oxide (ordinary lime) and liquid or vapor water for heat storage is described by Comstock and Wescott, Inc. (1959). Liquid water would be added to lime forming calcium hydroxide and liberating heat which could be used for heating. Electricity could be used for regeneration into lime and water. If water vapor and lime were used the weight would be considerably smaller because the heat of hydration with water vapor is considerably higher. The disadvantage of using water vapor is the requirement of large volumes of space for vapor passages. The systems using calcium oxide and water are among the smallest and lightest and involve very little hazard. The principle problem is the preparation of calcium oxide in a form capable of withstanding heating and regenerating without deterioration.

Comstock and Wescott (1959) also describe the heat of chemical change systems, such as the reaction of hydrogen with oxygen in the air. The release of heat could be regulated by passing small amounts of oxygen bearing air through a catalylic reactor giving off heat and water vapor. One of the problems to solve is the storing of large quantities of hydrogen. It cannot be stored at atmospheric pressure because of its large volume and it is not feasible to store it in high pressure cylinders. It has been suggested that hydrogen be stored in the form of a metallic hydride.

Electrical Energy Storage

Electrical storage batteries

Much interest has been developed recently in the application of electrical storage batteries for use in delivery trucks and small automobiles. Four firms are actively engaged in developing electric trucks, one of which is in production according to Hochgesang (1960). Ten firms have development projects for electric cars with production plans by five firms.

Many battery companies have been working in cooperation with firms interested in producing electric vehicles (Electrical World, 1959). The Exide Industrial Division of Electric Storage Battery Company designed batteries and aided on the first vehicles to appear last year, Cleveland

Vehicle Company's CV delivery truck. Last year twenty-five trucks were produced and the estimate for 1960 production is 800 units. The Gould-National Batteries firm is working on nickel-cadmium and silver-zinc batteries. Gould has explored the concept of electrical cars for about four years. The expense of the silver-zinc battery limits its use primarily to military applications. Scranton Cellomatic Battery Corporation has introduced interchangeable cells with base frames permitting an infinite number of cell arrangements. The wide voltage and amperage range plus the replacement feature holds promise for electric vehicle makers.

The Yardney International Corporation (Industrial and Engineering Chemistry, 1960) has worked with Professor Henri Andre, a French electrical engineer, in the development of rechargeable silver-zinc batteries. It has been tested for several years in an electrical car and has been used extensively for recent satellite, missile, and torpedo programs. The silver-zinc system yields a battery that is one-fifth the weight and volume of a lead-acid battery of equal capacity.

Many new miniature batteries which are being used today in industry are described by Gardner (1958). Miniaturized mercury and carbon-zinc dry cells are being used in hearing aids and wrist watches. The Elgin National Watch Company has developed an indium cell which resembles a standard mercury cell, in that it uses a mercuric oxide cathode. The anode is made of indium. This permits the cell to provide constant discharge voltage throughout its service life and is ninety-five per cent efficient. A new concept in battery development is the solid electrolyte battery. These are truly dry cells which operate by diffusion of ions through a solid rather than by movement of particles through a liquid or gas. Because there is no liquid in these batteries they have a very long shelf life and a wide range of operating temperatures. Although a solid electrolyte battery can be built which is less than one-thirtieth the volume of a standard cell, will last twenty times as long, has sixty times the voltage, its ability to deliver current is reduced by a factor of 10^7. The Naval Ordinance Laboratory's lead-alkaline cell is a primary cell that has been given rechargeability. It uses a lead monoxide-lead anode, a potassium hydroxide electrolyte and a silver cathode. The prototype model is just an inch in diameter and about one-half inch thick, has a nominal open circuit voltage of 0.90 volts and a rated capacity of 1,500 milliampere-hours.

Although there has been some improvement in electrical storage batteries the well known lead and sulphuric acid battery is still the most widely used and the least expensive. It has a limited life and requires care in upkeep. Cheaper storage batteries are needed for agricultural purposes in stationary locations. They do not need to meet the exacting specifications of the present automobile battery. They do not need to be compact and rugged for transportation or have to supply heavy currents of electricity for short periods of time. There are probably many other metals and metallic salts which could be used to develop storage batteries for agricultural purposes.

Solar cells

The Bell solar battery is an energy converter and not a battery for storing energy. According to Chapin, et al., (1955), it converts as much as eleven per cent of the energy it receives from the sun into electrical power. It is made of a number of individual silicon solar cells. The heart of the solar cell is the positive-negative (p-n) junction or boundry between the electrical conductivity types in a semi-conductor crystal. With suitable contacts and leads the solar cell can produce a current which can be used in an external circuit. Bell Telephone plans to use a solar battery to charge a storage battery which in turn will provide power for a complete terminal of a rural telephone system. The same solar cells have been used by Isaacs (1957) to supply energy to operate an electric fence charger in experiments at the Purdue University Agricultural Experiment Station. The solar cells are used to convert solar energy to electrical energy which is used to maintain the charge of a storage battery. The storage battery operates the fence charger on a twenty four hour basis whether the sun is shining or not. The solar cells alone cannot supply the high instantaneous current which the fence charger demands, but they can maintain a charge on the storage battery which can supply the peak demand. Forty-eight silicon solar cells are located on a glass enclosed frame atop the fence charger. The storage capacity of the storage battery is sufficient for at least ten days' operation without sunlight. Both lead-acid and nickel-cadmium cells have been used.

Researcher L. J. Giacoletto (1959) of Ford's Scientific Laboratory at Dearborn, Michigan, has outlined a plan for a new energy storage system which may have possibilities. Semi-conductor solar cells are used in the system to convert the solar energy collected upon rooftops in to direct current electricity. The electrical power is used to drive a direct current motor, which in turn is mechanically coupled to an alternator. During periods of high solar radiation, the alternator is driven at high enough speeds to feed power into the power lines to be used locally or to be delivered to the power lines for distribution. While the energy is fed into the power lines, the conventional kilowatt-hour meter is reversed in operation and kilowatt-hours are subtracted. Thus the storage method used in this system is the power distribution system which extends over wide areas of the United States. At present the cost of the solar cells makes this system prohibitive.

Although solar cells are very expensive for ordinary use the cost is primarily one of fabrication and will be greatly reduced when there is enough demand so that production techniques can be used.

Nuclear batteries

The possibilities of using batteries with a nuclear energy source were discussed by Dr. Linder (Science Digest, 1955b), of the Radio Corporation of America, at the Geneva Conference on the Peaceful Uses of Atomic Energy. He stated that electrical batteries of the future will be powered by by-products of atomic radiation converted directly into electricity. Radioisotopes from the debris of the U. S. atomic power reactors ten years from now might furnish the radiation that could be converted into electrical energy equivalent to two million watts from the annual production of batteries. The Atomic Energy Commission's Mound Laboratory at Miamisburg, Ohio, has already developed an atomic battery with a blistering hot core of radioactive polonium (Science Digest, 1955a). The battery applies the heat of its capsule core to forty thermocouples. These thermocouples convert the heat into tiny amounts of electrical energy. The battery uses a polonium heater of 4.65 watts and delivers a maximum electrical power of 0.0094 watts. This battery could be used in instruments where long life dependability is required. The outside of the battery is shielded from the 450° F. heart temperature so that no fingers are burned when it is handled.

Fuel cells

The fuel cell is a device which produces electrical power directly through chemical reactions. According to Douglas and Liebhafsky (1958) it is free of the Carnot cycle limitation on efficiency as heat is not involved. All of the electric energy delivered by the cell is converted into chemical energy and here the Carnot cycle limitation does not apply. Therefore it is readily possible to produce electrical energy at much higher efficiencies which may approach 80 to 90 per cent.

Liebhafsky and Douglas (1958) state that the thermodynamic advantages of the fuel cell have been known since the end of the last century but the first such device was demonstrated as early as 1846. Since that time several experiments have been conducted with fuel cells but only in the last few years has widespread interest been shown in this simple method of generating electricity.

Scientists in the research laboratories of National Carbon Company, a division of Union Carbide Corporation, have developed a fuel cell which converts chemical energy of gases directly into electricity (Power Engineering, 1957). Hydrogen and oxygen gases enter the cell through specially treated hollow porous carbon electrodes and diffuse to the surface where they come in contact with the electrolyte, a solution of potassium hydroxide. At the hydrogen electrode the electrochemical reaction releases electrons which flow through the external circuit and are accepted at the oxygen electrode. This flow of electrons is the current that powers electrical equipment. Ionic conductivity through the electrolyte completes the circuit and the water formed in the reaction passes from the cell in a hydrogen stream. The cell is designed to work at room temperatures and approximately atmospheric pressures. The water is disposed of by evaporation and the life of the cell is theoretically unlimited. Cells were operated in National Carbon's laboratory eight hours a day, five days a week for over a year with no signs of deterioration. The new fuel cell has an efficiency in the range of 65 to 80 per cent. The research and development indicate that the optimum fuel cell design will be one which will produce approximately one kilowatt of power from a package unit one cubic foot in volume. Voltage across the electrodes is about one volt, and by simply connecting a number of cells in a circuit any voltage desired can be obtained. The amount of electrical current produced by the cell depends on its physical size, so by varying the number and size of cells many combinations of voltages and currents can be obtained. Although pure oxygen is preferable for high current densities, the cell can be operated with hydrogen and air for producing smaller amounts of power. Also the cell can be operated with hydrogen containing considerable impurities which means that standard industrial grades of purity can be used.

A Cambridge, England, electronics firm has developed a fuel cell which mixes hydrogen and oxygen in the presence of a nickel plate in a solution of caustic soda (The State Journal, 1959). The cell yielded five kilowatts, or about seven horsepower. The cell itself was small but the control gear was rather large and bulky and weighed about 700 pounds.

There are many other companies and persons working on the development of fuel cells but possibly the most interesting is the Allis Chalmers fuel cell powered tractor described by Ihrig (1960). Allis Chalmers engineers have developed a fuel cell which uses a mixture of gases, largely propane and including oxygen. The individual units are one-fourth inch thick and twelve inches square and have an open circuit voltage of one volt. To power a tractor 1,008 of the cells were joined together to produce electricity to operate a standard twenty horsepower, direct current motor which was directly connected to the drive mechanism.

One of the problems of the fuel cell is to obtain the quantities of hydrogen and propane which will be needed. Although hydrogen is very plentiful, it is locked up in water and costs a considerable amount to set free. It is also possible that fuel cells will be developed that can use, in addition to hydrogen and propane, other hydrocarbon fuels which are more plentiful and cheaper to produce. Agricultural products might be a source of hydrocarbons which could be used in the fuel cell.

Moos (1960) states that the fuel cell can be used for ground power supplies, individual home or farm units where size and weight are not critical, and mobile power supplies for automobiles and other vehicles. The first market for fuel cells, he writes, will be industrially produced electrical power. The military applications are many and a number of developmental-type contracts have been awarded to some of the organizations working on fuel cells in the United States.

Storing Energy Mechanically

The Oberlikon Company of Switzerland has developed an application of flywheel storage for omnibus service

(Automobile Engineer, 1955). The storage of energy by means of a flywheel can be given by the equation

$$E = \frac{Iw^2}{2}$$

Where $I = Mk^2$
$M = W/g$
w = angular speed
W = weight
g = acceleration of gravity
k = radius of gyration

The flywheel developed for this gyrobus is five feet, four inches in diameter and is directly coupled to a propulsion motor which consists of three units, all of the squirrel cage induction type, assembled in a common housing filled with hydrogen at a pressure of ten pounds per square inch. A fifty cycle motor-generator is directly coupled to the flywheel which has a maximum speed of 3,000 rpm. The energy stored in the flywheel at 3,000 rpm is 24,000,000 foot pounds or 9 kilowatt-hours. The electrogyro can be fed from the normal 220 volt, three phase supply throughout the night. The energy required to keep it running throughout the night is equivalent to the energy required to accelerate the unit from 0 to 2,500 rpm. A period of about 20 seconds is required to increase by one kilowatt-hour the amount of energy stored and about two minutes is required to accelerate it from 2,000 to 2,950 rpm. The overall efficiency of the vehicle in terms of power input at the charging point to power output at the wheels is about 50 per cent.

The Northrop Corporation of Hawthorne, California, has designed a monorail train which uses a propulsion unit built by the Oberlikon Company as described by Freiday (1959). The monorail will be used for a one mile trip between downtown Seattle, Washington, and that city's Century 21 exposition which opens in 1961. A 1,000 pound inertia flywheel set in motion by a station power source obtains a speed of 440 rpm and turns a generator which provides current for traction motors until the next stop. On long runs the flywheel can pick up energy from a powered rail along the route without stopping. Actual operating speed in a transit system would probably be about 68 miles per hour peak on a mile run with the top design speed of 150 mph.

Professor C. K. Razak of the University of Wichita proposes that a gas turbine be cut in two and used to store and generate power (Popular Science, 1959). Air could be pumped into a natural underground cavern or abandoned mineral mine with the compressor unit during slack hours. The compressed air could be tapped to run the turbine unit and a generator during peak times of the day. The turbine would give three times the power obtained when burning fuel as no power is being diverted to turn a compressor.

Voysey (1958) writes that although compressed air is not as versatile as electricity it can be stored compactly. It could be stored in steel tubing or tanks. At twenty atmospheres pressure ten cubic feet of storage volume would contain about one and one half pounds of air which could be displaced and expanded in cheap turbines to provide up to one kilowatt-hour of energy. Underground air storage in rock caverns, salt mines, mineral workings, and sand or gravel beds in the form of lenses or domes sealed with impervious strata would be safe and possibly economical. Cavities at a 700 foot depth would be needed for operation at twenty atmospheres pressure.

Greer (1953) describes another way in which compressed gas is used to store energy. A hydropneumatic accumulator is a mechanism in which potential energy is stored in an enclosed gas chamber contained within a fluid chamber. Gases have a high degree of compressibility and can store energy when merely compressed. Combining liquids and gases in controlled volumes produces a hydropneumatic accumulator whose dynamic energy can be used to do work. For intermittent work cycle motions the accumulator can be used as a storage battery to provide the source of energy, a pump being used simply as a means of storing energy in the accumulator. It can also be used as an extra source of power to supplement the output of the pump during peak demands beyond the capacity of the pump.

The pumping of water during low demand periods to a high level reservior can be used to store energy for peak demand periods. There are some areas in which geological features can be used to store water in a reservoir at the top of an unused mine shaft. At 1,000 feet of head about fifty cubic feet of water must be stored to provide a kilowatt hour of power. Several pumped water storages have been built throughout the world. Armbruster (1960) says that the first one in the United States was built on the Rock River in Connecticut. The storage had a 400 foot head. Another project is being built near Lesterville, Missouri, for the Union Electric Company (Electrical World, 1960a). About three kilowatt-hours of nighttime generation will be required to pump the water for two kilowatt-hours of daytime production.

ENERGY SOURCES OF THE WORLD

Since man is a user of enormous quantities of energy it is desirable to know how much and what kinds of energy will be available in the future. By knowing this information, one may gain some insight as to which general direction research activities should be directed.

The sun has been the ultimate source of all the energy received on the earth. The fossil fuels, which are the main source of energy at the present time, are the result of plants capturing and storing energy thousands of years ago. The hydroelectric power generating plants use the potential energy of water which undergoes a continuous cycle caused by energy from the sun. The supplies of fissionable materials capable of producing large quantities of energy also came from the sun when the earth originated.

Reserves of Capital Energy

The reserves of most fuels are difficult to measure or estimate. Even if an approximate estimate of fuel sources is known, these fuels may never be used because they are not economically recoverable. Various estimates of the world reserves of coal have been made. Putnam's (1953) estimates of the economically recoverable coal reserves appear to be the most realistic figures to present here.

Table 1. Estimates of economically recoverable coal reserves of the world, 1950

Country	Heat content 10^{18} Btu
United States	6
Canada	2
United Kingdom	1
Other (Western) Countries	7
China	6
U.S.S.R.	10
Total	32

Adapted from Putnam (1953)

The total world use of coal has amounted to 213 Q (1 Q = 10^{18} Btu) one half of it since 1923.

The total estimates by Putnam (1953) of oil and gas are 5.04 X 10^{18} Btu as given in Table 2.

Table 2. Economically recoverable reserves of oil-gas

Country	Proved reserves 10^{16} Btu (1950)	Undiscovered 10^{16} Btu	Total 10^{16} Btu
United States	25	25	50
Rest of Western Hemisphere	11	90	10
Soviet Union	4	130	134
Middle East	57	110	167
All other regions	2	50	52
Total	99	405	504

The term "economically recoverable" is used to mean recoverable at costs no higher than 1.3 times 1950 costs for oil-gas, and at costs no higher than twice 1950 costs for all other fuels.

Liquid fuels can also be obtained from the so-called oil-shales. Oil-shale is a rock containing ten per cent or more of hydrocarbons. The rock is mined, crushed, and heated and yields from sixty gallons of crude oil per ton down to ten gallons per ton according to Thirring (1958). According to Ayres and Scarlott (1952) the only areas where considerable oil-shale reserves exist are in the United States and Brazil. Table 3 gives the distribution by country with a total estimate of 668 X 10^9 barrels of recoverable oil.

Table 3. Potential oil-shale reserves of the world

Country	Oil-shale 10^{19} Ton	Recoverable oil 10^9 Barrels	Heat content 10^{15} Btu
United States	700	265	2116.19
Brazil	550	300	1739.33
Sweden	5	1	5.79
Estonia	1.5	1.5	8.70
Manchuria	0.5	0.1	0.58
France	0.06	0.03	0.174
Australia	0.04	0.06	0.348
Tasmania	0.009	0.002	0.012
Approximate total	1257.000	668.000	3871.000

Adapted from Ayres and Scarlott (1952).

From these reserves an energy content of approximately 3.87×10^{18} Btu can be expected if the same specific heat content as crude petroleum is used. Putnam's (1953) estimate is only 1×10^{18} Btu as he discards as economically not recoverable all shales with an oil content below thirty gallons per ton.

The naturally occuring tars are deposits containing a semi-solid sticky substance mainly composed of higher hydrocarbons similar to the by-product tars of petroleum and coal. No practical means of removing tar from many of the deposits in Venezuela, Mesopotamia, and the United States is known. Large tar-sand deposits along the Athabasca River, in north Alberta, Canada are said to contain up to 300 billion barrels of crude oil. If only that portion which yields thirty gallons per ton as a minimum is considered as economically recoverable, the heat content of the reserves in the Athabasca area does not exceed 0.20 Q ($1 Q = 10^{18}$ Btu). All other tar deposits are much smaller.

Total reserves of fossil fuels

The total reserves of fossil fuels are summarized in Table 4.

Table 4. Heat content in the world reserves of economically recoverable coal, oil and gas, oil-shale and tar-sand

Coal		32.0 Q
Oil and gas		5.04 Q
Oil-shale		3.87 Q
Tar-sand		0.02 Q
	Total	40.93 Q

A further reduction would be made in this total if the reserves of petroleum are depleted and considerable amounts of fluid fuels are made from coal, in a process which involves considerable fuel losses.

Energy from Nuclear Fuels

Fission power

The design of nuclear fission reactors has improved greatly in the last decade. As more knowledge is obtained and new designs are adopted the cost of producing electricity and heat will continue to drop. Experts of the OEEC (Organization for European Economic Cooperation) predict that nuclear power construction and fuel costs will drop faster than those of conventional thermal stations and that nuclear fission power will become competitive toward 1970-1975 (Electrical World, 1960b). In other areas the time at which nuclear fission power becomes competitive may be slightly sooner or possibly much later depending on local fuel supplies and costs.

The amount of energy available in fissionable uranium and thorium is estimated by Meir (1956) to be more than 1,000 times as great as the conventional fossil fuel supply. According to Weinberg (1960) there are enormous quantities of thorium and uranium dispersed in trace amounts throughout the crust of the earth. Existing technology could be used to extract the energy of the rocks. Brown, et al, (1957) say that from one ton of granite an energy equivalent to fifteen tons of coal can be economically extracted. With the use of "breeder" reactors coming into use, which breed more fuel than they consume, the supplies of fissionable fuels will be extended much farther. Weinberg (1960) writes that there is no longer any doubt that nuclear breeding offers a long-term solution to the energy problem.

Arley (Michigan State News, 1960a), in expressing a more pessimistic point of view, says that it is unlikely that nuclear reactors will ever produce electricity on a world-wide scale. The greatest drawback of fission power is that it creates dangerous radioactive waste materials. He states that if fission were used on a world-wide scale there would be so much waste that not all the oceans could dilute it sufficiently.

Fusion power

Since the concept of the fusion bomb came into being research has been directed toward using the fusion process in a controlled reaction to produce heat and electricity. Progress in the thermonuclear field is still in its childhood stages. Allis (1960) compares the present state of thermonuclear research with the art of flying a hundred years ago. He does not believe thermonuclear energy will have practical application in this century.

If controlled fusion can be successfully developed there is enough deuterium (heavy hydrogen) in the oceans of the world to supply the demand for energy for the life time of the solar system. Hurwitz (1958) writes that one gallon of ordinary water contains enough deuterium to provide energy equivalent to 350 gallons of gasolene or approximately 43×10^6 Btu. This is despite the fact that deuterium constitutes only about one part in 6,000 of the hydrogen in ordinary water. Separating the deuterium from the ordinary water can be done at a very nominal cost says Hurwitz.

It is not yet possible to assume that successful thermonuclear reactors can be built. Arley (Michigan State News, 1960a) says that the best calculations at present indicate there is only a 50-50 chance that fusion will produce more energy than it requires to start the process. He also says that engineering problems may never be solved.

Allis (1960) is more optimistic and estimates that it will take ten years to reach the break-even point where the energy obtained equals that required to start the process. Even if this is accomplished it may be many more years before fusion power is competitive with other power sources.

Income Sources of Energy

Among the feasible income sources of energy are solar collectors, water power, vegetation, natural steam, tides, wind power, temperature differences in tropical water, peat, and farm wastes.

Water power

The total available water power capacity of the world based on a continuous output at low water without storage is given in Table 5.

Table 5. Available water power capacity

Area	Available capacity million kilowatts
Eastern U.S.S.R., India, China, Japan, Australia, and New Zealand	100
North and South America	104
Europe, European Russia, the Middle East and Africa	175
Total	379 million kilowatts

Compiled from estimates made by Putnam (1953)

If storage and more complete development take place, an installed generating capacity of 2,000 million kilowatts might be possible. At a 50 per cent load factor this would yield 1,000 million kilowatt-years or $3 X 10^{16}$ Btu per year. The 1950 installed water power capacity was 75 million kilowatts. If a five-fold increase in installed capacity is realized by 2000 A.D., the total cumulative contribution to the world energy system from water power would amount to a little less than 0.2 Q. In the United States water power in 1950 contributed about one per cent of the total energy in the system. It is estimated that water power will never provide more than a few per cent of the United States energy load.

Direct solar energy

Although the sun is the primary source of all our energy very little use is made of it directly. An increase in the costs of conventional fuels may result in the use of much more of the direct solar energy. Yellott (1957) gives the rate at which solar energy reaches the earth's atmosphere as approximately 451 Btu per square-foot-hour. The direct radiation reaching the earth's surface may range from 250 to 320 Btu per square-foot-hour on a clear day. He states that the United States receives more than $30 X 10^{18}$ Btu, or 700 times our present energy use. To make extensive use of solar energy huge collecting surfaces would be necessary to obtain useable quantities because of its diffuse nature. At present the cost of energy collectors prevent its use except for specialized purposes in certain areas. It would be desirable to obtain large quantities of electricity from solar energy but the big drawbacks are the low conversion efficiencies obtained and the high capital costs of energy converters to cover large areas. The major purpose for which solar energy can be used in the near future is for space heating. Approximately one-third of the energy used in the United States is used for space heating and one-fifth of the space heating is home heating. The low temperature heat obtained from solar collectors could be readily used for home heating in areas which receive large quantities of sunshine.

Ayres and Scarlott (1952) estimate that 2.3×10^{16} Btu per year of solar energy are available for space heating and that as much as 7.6×10^{15} Btu per year may be used by 2050 A.D. They estimate that the maximum energy available that could be converted to power with solar collectors is 4.325×10^{16} Btu per year and that as much as 5.09×10^{16} may be used by 2050 A.D. in such a manner.

Rotational energy-tides

The earth was endowed with an enormous amount of rotational energy when it was created. A portion of this energy appears as ocean tides. The amount of tide energy is vast but the prospect for the future is that only three-tenths of one per cent of the potential can be captured for use according to Ayres and Scarlott (1952). Putnam (1953) gives the tide energy dissipated as 3×10^{16} Btu per year. Therefore 9×10^{13} Btu per year could possibly be obtained from tidal power projects.

There are several potential tide power project locations which have received considerable interest. These are the Severn River in southern England; the Passamaquoddy Bay, near Eastport, Maine; the Rance River and Mont St. Michel on the shores of Brittany in northern France; the Bay of Fundy in Canada; the San Jose and Qeseado Rivers of Argentina; and the Kola Peninsula, the Mezen Gulf, and the Sea of Okhotsk in the U.S.S.R.

The French government is constructing the power project in Brittany at a cost of $70 million (Water Power, 1960). It will have a capacity of 342,000 kilowatts.

The British are also seriously considering the development of the Severn project because of its potential of producing two billion kilowatt-hours per year.

Meir (1956) estimates that no large scale contributions will be made by tidal power projects, but that there are interesting opportunities for providing approximately 10^7 kilowatts of installed power capacity.

Wind power

There are a few areas on the earth where wind could supply a nearly constant source of power. Some of the potential sights are in Great Britain, Denmark, South Island of New Zealand, Southern Chile, Japan, and Russia. Putnam (1955) describes the earth's winds as a rotating, regenerative, thermal engine, fueled by radiant energy from the sun. There are several different wind power generating plants operating throughout the world. A mean annual wind velocity of twenty five miles an hour at hub height of the wind turbine is required if a wind power installation is to compete economically with conventional power systems in the United States.

Putnam (1955) estimates that the ultimate installed capacity of large wind turbines in windy regions close to growing demands for energy may amount to 100 million kilowatts. Medium and small units may amount to as much again. If used an average of 4,000 hours a year the 200 million kilowatt installed capacity would produce a total of 27.3×10^{14} Btu per year.

Earth heat

Ayres and Scarlott (1952) write that the earth radiates more heat than it receives from the sun. Although the source of earth heat is not certain, the flow of heat out from the earth's crust has been estimated at a little less than 1 Q per year, or about ten times the present requirement of the world energy system.

Engel (1959) writes that plans have been made by American scientists to drill a hole several miles into the thick band of hot rock surrounding the earth's molten core. In the future this might prove to be a nearly inexhaustable source of energy.

In Iceland natural hot springs are used as a primary source of heat for several cities according to Whatley (1957). A central pumping and distribution system is supplied with hot water from nearly one hundred bored wells. There are a few other areas where natural heat is released in a concentrated enough form such that it could be used profitably. One of these is a canyon one hundred miles north of San Francisco which is full of hot springs and geysers (Michigan State News, 1960b). A 3,200 acre area has been leased and it is reported that steam from four wells will be piped to a new power plant built by Pacific Gas and Electric Company to produce electricity on a commercial basis. The total contribution to the world energy system that can be expected from earth heat is very small.

Fuel wood

In 1950 fuel wood contributed about 4×10^{15} Btu to the world energy system, according to Putnam (1953), or about four per cent of the total. The high demand for wood for other purposes such as lumber and pulpwood makes only about one-half of the total production available for fuel. Putnam concludes that if the world's forests were all restored and kept under productive management, and if one-half of the wood were used for fuel, the annual input to the energy system would be 90 X 10^{15} Btu.

Farm wastes

Putnam (1953) writes that until as recently as 1940 more energy was obtained from farm wastes than from all the fluid fuels. He estimates that between 10 and 20 per cent of the world energy is supplied by farm wastes. In India dung cakes are a major source of fuel as is wheat in Argentina. It would be desirable to return much of the waste back to the soil to retain its fertility, but possibly certain types of wastes such as straw, corn stalks, etc., and specially developed plants could be used to produce fuel for agricultural uses. Putnam estimates the present contribution to the world energy system from farm wastes is 18 X 10^{15} Btu per year.

Peat

Although peat is a fossil fuel, it grows and can be harvested as a crop. Managed peat bogs could be put on a sustained yield basis. The Btu value of peat is about one-half that of coal. According to Ayres and Scarlott (1952), sixty per cent of the known peat bogs are located in Russia. Many other countries have small peat bogs with the United States having one-tenth of the world's peat (primarily in Minnesota). Putnam (1953) estimates that if peat were produced under good management a yearly yield of 14×10^{15} Btu could be obtained.

Temperature differences in tropical waters

In a few areas of the world oceans there are warm surface waters which are not far from a source of cold water. If the temperature differential is great enough power can be generated on a small scale. The French government is constructing a power plant of this design on the west coast of Africa at Abidjan, according to Ayres and Scarlott (1952). The plan is to use surface water with a mean annual temperature of 86° F. to produce steam by drawing it through vacuum pumps. The steam would pass through steam turbines to produce power, and then be condensed with 44° F. water pumped up from the bottom of the ocean. Ayres and Scarlott estimate that there are 20,000 miles of ocean shore line where the temperature differential is great enough to operate a steam turbine. They estimate that it would be feasible to expect an annual production of 3.4×10^{15} Btu if properly harnessed.

Atmospheric electricity

Ayres and Scarlott describe four varieties of atmospheric electricity. Lightning, which can be readily seen, strikes the earth approximately one hundred times per second. The total energy in a lightning stroke is about one kilowatt-hour. If all the lightning strokes could be collected into a continuous flow of electricity approximately 30 million kilowatt-hours or 10.24×10^{10} Btu per year would be obtained.

The other three forms of energy are difficult to find and measure and no method has been found to collect any of the atmospheric energy.

Higher plants

The higher plants are the major source of food for nearly all animal life. In many areas of the world there are food shortages for large numbers of people. It appears that nearly all of the energy obtained from the higher plants will be needed just to feed the world population.

Ayres and Scarlott (1952) state that the world has 2.6 billion acres of land suitable for intensive farming. Putnam (1953) assumes that the world has 10 billion acres of reasonably good agricultural land. He states that the earth could support 3.5 billion people if yields equal to the United States averages were obtained. If yields were as heavy as much European land 5 billion people could be supported. If in addition tropical wet lands were brought into production and all land yielded equal to the best yields today, the earth could support 10 billion people.

Computations made from data presented by Willkie (1942) indicate that the energy obtained from sugar beets grown on one acre of land would be 269 X 10^5 Btu if processed into alcohol. The computations for other crops are given in Table 6.

Table 6. Energy in alcohol obtained from farm crops

Crop	Yield	Gallons alcohol	10^5 Btu per acre
Sugar beets	15 ton/acre	331.5	269
Corn	100 bu/acre	235	191
Sweet potatoes	250 bu/acre	235	191
Potatoes	250 bu/acre	172.5	140
Wheat	30 bu/acre	72	58.5

If it is assumed that the world has 10 billion acres of cropland and all of it produces wheat yielding thirty bushels per acre, the energy in alcohol obtained from this wheat would be approximately 5.85 X 10^{16} Btu. If the wheat were used directly as a fuel the energy obtained would be approximately twice this value or 11.7 X 10^{16} Btu. This would supply about one-fourth of the annual energy used in the world.

The world population in 1950 was estimated to be 2.3 billion according to Putnam (1953), and he estimates that it will be 3.7 billion in 2000 A.D. and 6 billion in 2050 A.D. With such huge demands for food nearly all of the cropland of the earth will be needed for maximum food production and the higher plants cannot be expected to contribute significantly to the energy system of the world.

One other method which might be used to obtain energy from plants is the possibility of using their electrical potential to supply energy to a closed circuit. Burr (1956) wrote that in his studies it was determined that trees had electrical potentials. If plants could be found which would convert energy from the sun into electricity in useful quantities, they might supply a very small amount of energy for special purposes.

Controlled biological synthesis

There have been a number of studies conducted in which single-celled algae were used to collect solar energy. Myers (1956) describes the two operations which the algae cell performs. One is the accumulation of carbon, nitrogen, and inorganic salts. The second and more important is the conversion of kinetic energy of light into potential chemical energy by photosynthesis. The production of algae in shallow solutions is said by Ayres and Scarlott (1952) to be capable of absorbing two per cent of the solar energy falling on it. Of the many species of algae, Chorella has been studied in most cases. It is produced in a continuous process and yields of 75 to 100 tons per acre, dry weight, are expected. Fisher (1956) estimates that the minimum selling price for bulk dry algae would be between $0.19 and $0.41 per pound. Putnam (1953) states that with such prices the energy from algae would cost approximately 150 times as much as the energy from coal. If Chorella-fuel were used to produce electricity in a steam plant the electricity would cost 40 to 50 times as much as from a coal burning plant.

It is possible that large acreages of arid land could be used for producing Chorella-fuel on a large scale but the cost would be phenomenal. Therefore it is not probable that algae will contribute significantly to the energy system of the world in the near future.

Total income energy

The annual energy which can be obtained from income sources is given in Table 7.

Table 7. Annual income sources of energy

Source	Maximum energy available, Btu	Used in 1950, Btu	Possible in 100 years, Btu
Water power	3×10^{16}	0.25×10^{16}	2.54×10^{16}
Solar collectors	4327×10^{16}	Trace	5.85×10^{16}
Fuel wood	20×10^{16}	4×10^{15}	9×10^{16}
Farm wastes	20×10^{15}	18×10^{15}	15×10^{15}
Wind power	51×10^{14}	Trace	27.3×10^{14}
Peat	14×10^{15}	Trace	2.5×10^{15}
Earth heat	1×10^{18}	Trace	5×10^{15}
Tides	3×10^{16}	---	13×10^{13}
Tropical waters	3.4×10^{15}	---	Trace
Atmospheric electricity	2.5×10^{16}	---	---
Biological synthesis	?	---	---
Higher plants	12×10^{16}	---	---
Approximate totals	4454×10^{16}	25×10^{15}	20×10^{16}

The total given in the column under maximum energy available is more than enough to supply the demands of the world energy system for several centuries. There are some complicating factors which make most of this energy unobtainable. In several cases, such as tropical waters, earth heat, and solar collectors, the economics of production will allow only small portions of the total energy available to be obtained. In other cases, such as atmospheric electricity and tides, the necessary technology has not been developed which will enable the energy to be collected and used.

PROCEDURE

An energy efficiency and use chart will be developed to make it simpler to see the relationship between the various sources and many uses of energy. The information presented on the chart will be obtained from several sources as will be indicated. In those instances where necessary information cannot be found or where a range of values is given, the values used will be assumed to adequately represent actual situations.

Because of the large quantity of information it will be desirable to present it as two figures. The methods which are or can be used to utilize the energy obtained directly from the sun will be illustrated. The efficiencies of the conversions and storage processes through which the energy goes will be given for several different methods of energy use. The methods which can be used to utilize energy from the major fossil sources of fuel will be presented. The efficiencies of the conversion processes will be included.

The 1958 average wholesale fuel costs in the United States will be presented. They will be compiled primarily from data given in Table A-1 of the Appendix. Wholesale energy prices will be used for most of the examples discussed here because of the wide variation in retail price. This variation is largely due to transportation costs. If retail prices are desired Figure A-1 in the Appendix, which gives energy transportation costs, can be used to obtain rough estimates. In addition, the wholesale price indexes given in Table A-2 in the Appendix enable the use of fuel prices obtained from different years to be put on an equal basis.

The data from the figures and tables will be used to illustrate those areas where energy storage units might be used and the approximate monetary values which can be used to operate and construct such storage units.

RESULTS

Applications Using Energy Storage

Economy of using solar energy as electricity

According to Giacoletto (1959) the average yearly solar energy flux for the Detroit area is 1,347 kilowatt-hours per square meter or 125 kilowatt-hours per square foot. The average annual farm consumption of electricity for 1958 as given in Farm Power (1960) is 3,816 kilowatt-hours. In some of the more prosperous farm states the average annual farm consumption is approximately 6,000 kilowatt-hours, and this will undoubtedly increase as farms become more mechanized. If a total conversion efficiency of 8.25 per cent could be obtained as indicated in Figure 1, the required collector area to produce this power from solar cells would be approximately 582 square feet. The yearly value to the consumer of 6,000 kilowatt-hours at 2.5 cents per kilowatt-hour is $150.00 based on conventional electrical power costs. The yearly value to the average farm consumer of the 3,816 kilowatt-hours used is $95.40. Therefore the average consumer might easily justify spending this amount each year for an electrical system which would supply the electricity in the amounts and at the times desired. As the operational costs would be negligible, over a ten year period $954 could be spent for maintenance or depreciation.

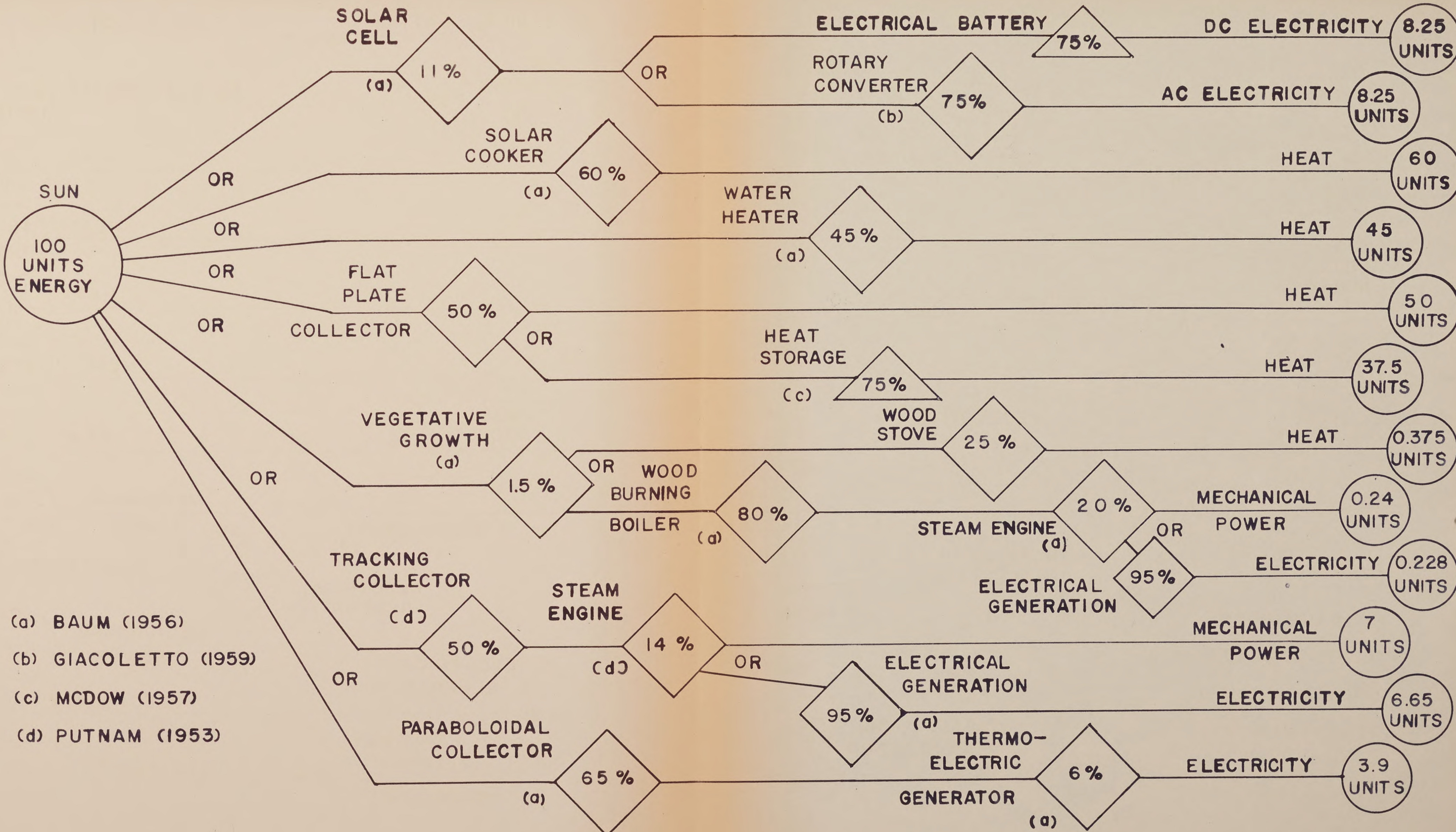

FIGURE I. EFFICIENCY OF USING ENERGY DIRECTLY FROM THE SUN

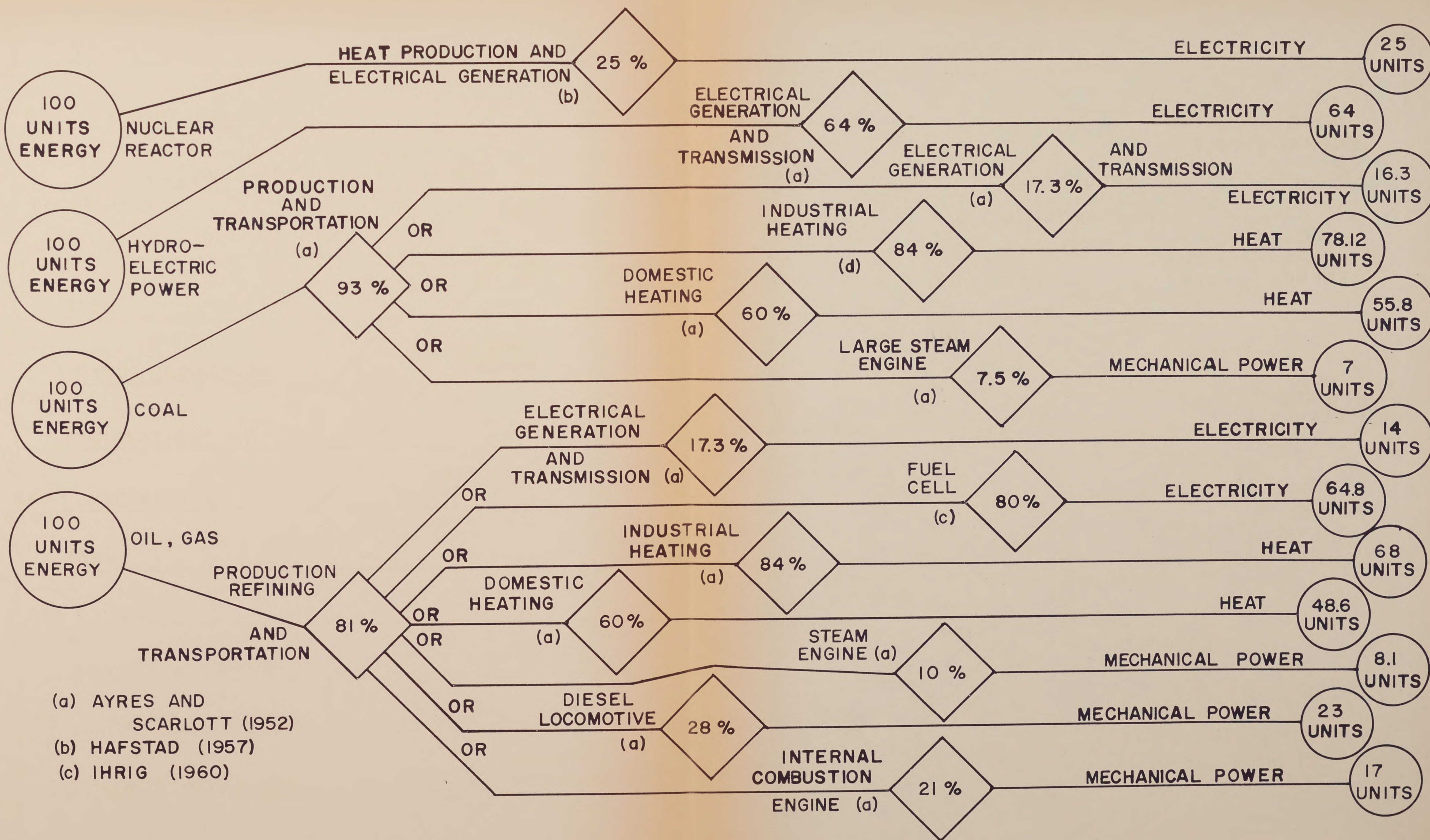

FIGURE 2. EFFICIENCY OF USING ENERGY FROM FOSSIL SOURCES AND HYDROELECTRIC

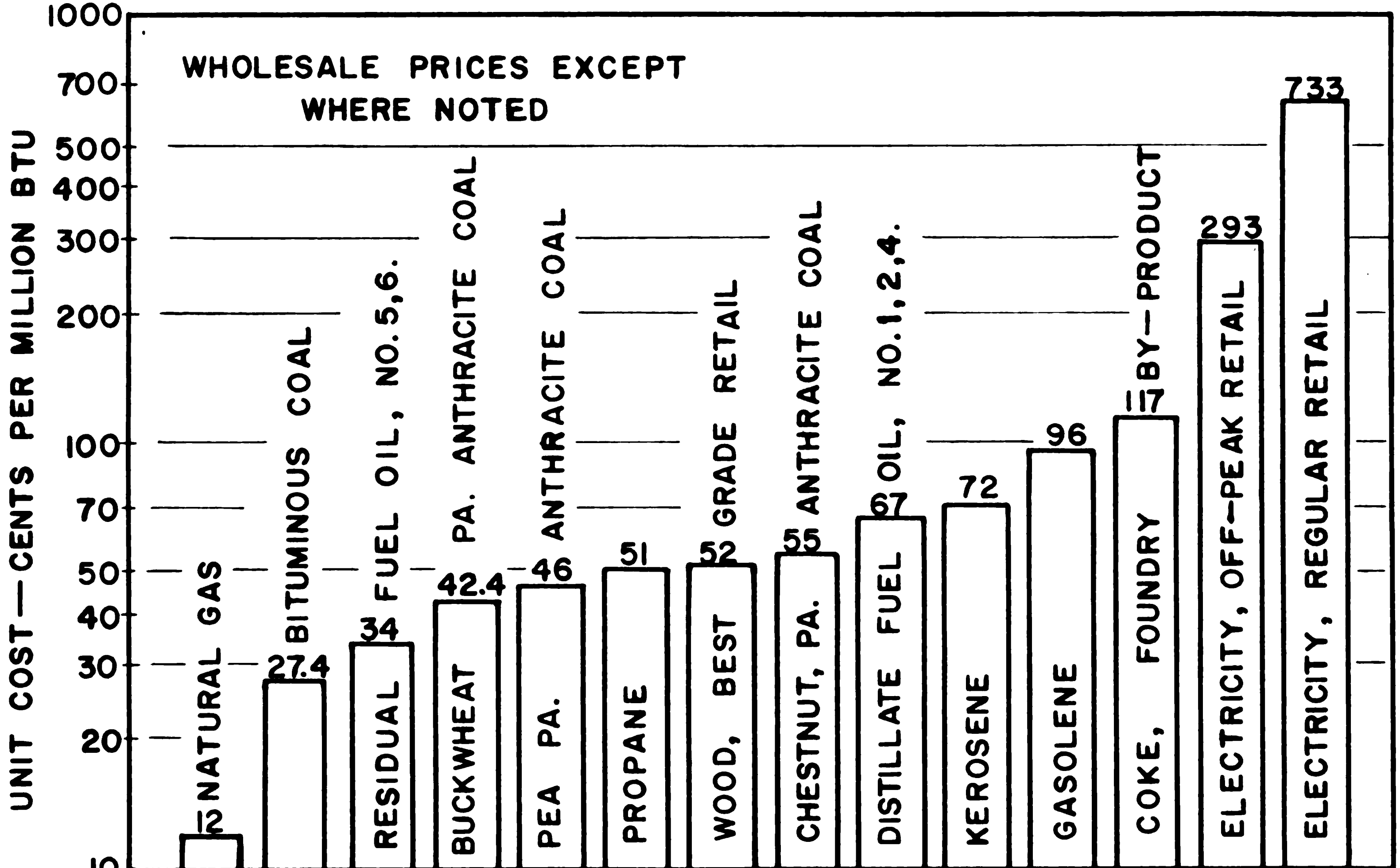

FIGURE 3. 1958 AVERAGE FUEL COSTS IN UNITED STATES

One of the major problems would be designing the system with the ability to provide electricity when desired. For this reason a storage unit would need to be included. At the present time the cost of the 582 square feet of solar cell collecting surface would be prohibitive. If a storage unit was included in the system the cost would be higher yet because a larger collecting area would be necessary due to the energy loss of the storage unit. With the cost of the storage unit and the rotary conversion equipment in addition to the collecting surface it does not appear likely that electricity obtained in this manner can be competitive where conventional sources of electrical power are available.

In locations where power is difficult to obtain the solar cell might be used for special purposes. Unless the cost is greatly reduced or conversion efficiencies are considerably improved solar cells will not be commonly used while the conventional sources of energy are still plentiful.

Storing off-peak electricity for space heating

In many areas power companies sell electricity during off-peak periods of the day for less than one half the regular rate. The off-peak period usually occurs between approximately 9:00 P.M. and 6:00 A.M. It is quite possible that economical storage units could be developed which could be charged during the off-peak period and used for space heating during the peak period. If such a unit would make space heating less costly and would be simple and convenient to operate it might serve in many space heating installations.

The following example will indicate the economic requirements of an off-peak storage unit.

Size of storage required for one family: assume one
million Btu per day

Cost of electricity:

off-peak, assume one cent per kilowatt-hour or
from Figure 3, \$2.93 per million Btu

regular, 2.5 cents per kilowatt-hour or from
Figure 3, \$7.33 per million Btu

Efficiency of storage unit--75 per cent

Cost of one million Btu to storage unit--\$2.93 per day

Cost of energy if bought directly as needed--750,000
Btu--\$5.49

The dollar value which could be used for operation and depreciation of a storage unit with the above assumptions is the difference between \$5.49 and \$2.93 or \$2.56 per day. If the heating season were 100 days long this would amount to \$256.00 per season.

Storage unit for nuclear reactor power

Energy from nuclear reactors will not become competitive with other forms of energy for several years although much interest and support have been shown in its development because of the promise it holds for the future. The price of electricity obtained from nuclear reactors is not expected to be a great deal higher than electricity obtained from oil and coal burning plants. To enable this to happen it will be necessary to develop a means by which a constant electrical load can be connected to the nuclear power producing system. The load factor of many of the present electrical systems does not exceed 50 or 60 per cent. With the complex system of electrical demand loads that exists there is little chance that a demand load even approaching 100 per cent will be attained. But such a load will be needed if ever nuclear power stations supply the bulk of the electrical energy.

Here is an area where energy storage systems on a large scale might be put to use because of the base-load character of nuclear power stations. The action of nuclear reactors cannot be economically arbitrarily increased or decreased to meet demands as can be done for coal burning plants. The storage systems would, therefore, need to be designed so that off-peak excess energy could be used to help supply energy for peak demand periods. This would probably involve storage only for daily peak periods, but it might also be feasible to store energy for seasonal peaks.

For illustrative purposes the following assumptions are made for a nuclear power producing plant:

Capacity--one million kilowatts

Demand load:

	10^6 kilowatts	10^6 kilowatt-hours
8 hours	0.4	3.2
8 hours	0.6	4.8
4 hours	1.5	6.0
4 hours	2.0	8.0
24 hours		22.0 X 10^6 kilowatt-hours

Energy storage unit--8 X 10^6 kilowatt-hours or 27.3 X 10^9 Btu

Storage efficiency--75 per cent

Energy obtained from storage--6 X 10^{16} kilowatt-hours or 20.5 X 10^9 Btu

Value of energy--one cent per kilowatt-hour or $2.93 per million Btu

Value of energy stored--$60,000

Value of energy produced and sold directly--$160,000

In this example, with a suitable storage unit, $60,000 worth of energy could be stored for less than twenty four hours and used to supply peak demand loads for an eight hour period. Without a storage unit the $60,000 worth of energy would be lost since the electrical demand would be less than the production capacity for sixteen hours a day.

Solar energy for space heating

Space heating is one use for which solar energy can easily be adapted. In many areas where seasonal heating is needed, energy storage units would be necessary to supply heat for cloudy days and night use. An alternative to the storage unit would be to have another heating system which could be used when solar energy is not available. The amount which could be spent for a storage unit as compared to a fuel oil heating system will be indicated in the following example:

Assume daily heat load--750,000 Btu

Efficiency of storage unit--75 per cent

Wholesale fuel oil cost would be 67 cents per million Btu (Fig. 3)

If 750,000 Btu of useful heat are needed, according to Figure 2, which gives 48.6 units of heat for each 100 units of oil, fuel oil containing 1,540,000 Btu would need to be purchased.

Cost of fuel oil--1.54 million Btu times 67 cents per million Btu equals $1.03 per day.

If the heating season were 100 days long this would amount to $103. Because operation costs would be negligible this amount could be used each year for maintenance or depreciation.

Solar energy for water heating

The most common methods of heating water for home and dairy use are electrical and gas. In the southern states solar energy has been used in a number of instances to heat water. This method could be used in many areas and an indication of the cost is given by the following example.

Assume that an electrical heater raises the temperature of fifty gallons of water per day from 60° F. to 160° F. This would require approximately 400 Btu per °F. or a total of 40,000 per day. With electricity costing $7.33 per million Btu the daily cost would be $0.29. If the solar heating unit could be used 250 days a year the energy would be worth $73.30. Therefore if a water heater using solar energy could be constructed and operated for $73.30 or less a year it would prove worthwhile.

Summary of energy storage applications

The results of the computations made for the illustrative examples of energy storage applications are listed in Table 8. Since the values used in the examples were assumed, the results only indicate approximate points to start from when designing systems for testing or use.

Table 8. Energy storage applications

Application	Yearly value	Remarks
Solar energy as electricity	$95.40	3,816 kilowatt-hours consumed per farm per year
Off-peak electricity for space heating	$256.00	100 day heating season One million Btu per day
Nuclear reactor storage unit	$60,000 per day	One million kilowatts, capacity of plant
Solar energy for space heating	$103.00	100 day heating season One million Btu per day
Solar energy for water heating	$73.30	50 gallons of hot water heated 250 days a year

The several systems will have to be designed, constructed, and tested before actual costs can be determined. Those systems whose yearly costs fall somewhere near the values given in Table 8 would be worthy of more complete development and testing. If energy storage systems can lower the cost of energy for agricultural purposes, or enable the farm producer to utilize new energy sources, the development of such systems will be worthwhile.

Level of Energy Determined by Use

In most instances the purpose for which energy is utilized determines the necessary level of energy. The temperature of heat utilized for many processes is particularly critical. For instance, heat which is used for crop drying should be heated a minimum of 20° F. above the ambient air temperature. This would indicate that 75° F. air in mid-summer would need to be heated to 95° F. for grain or hay drying, which can readily be done with solar energy collectors. House heating would require minimum temperatures of 70° F. and if storage units were included much higher temperatures would be desired. The heating of water for home and dairy purposes would require higher temperatures, probably in the range of 140° F. to 160° F.

Electricity, one of the higher forms of energy is the most flexible form and in many areas the most expensive. It can easily be converted to heat, with a conversion efficiency of virtually 100 per cent, at temperatures readily controlled over a wide range of values.

CONCLUSIONS

Energy Resources

The supplies of fossil fuels are being depleted much faster than they are being restored. The rate of annual use, approximately 0.4 Q, is increasing rapidly. Although it is difficult to estimate the size of the world fuel reserves it is believed that a production peak will be reached within the next fifty years. The supplies of petroleum will be the first to be exhausted, with coal sometime later. Undoubtedly if the world population and standard of living continue to increase we will have to depend less on our dwindling reserves of fossil fuels and more on other sources of energy.

The reserves of nuclear fuels are believed to be many times those of the fossil fuels. The technical aspects of obtaining energy from nuclear fission have been successfully solved. It is primarily a matter of time before nuclear power becomes economically competitive with other energy sources.

If the technical aspects of obtaining useful energy from nuclear fusion can be solved, an almost unlimited source of energy will be available. As of now we cannot rely on energy from nuclear fusion as there are many problems yet to be solved.

The income sources of energy can, if properly developed, contribute significantly to the world energy system. Water power, fuel wood, and farm wastes will continue to contribute a small but significant amount to the energy system. The sun is the primary source of all our energy. This source, along with nuclear power plants, will have to supply the bulk of the energy in the future. There are many possibilities for developing methods of using energy directly from the sun. These developments depend primarily on economics. When the conventional sources of energy become scarce and expensive man will turn to the sun for energy but not until then will he do so on a large scale.

Energy Storage Applications

The possibility of using off-peak electricity for space heating shows considerable promise. According to computations approximately \$250 a year are available which could be used to construct and operate a house-heating energy storage unit. The storage would need to be safe, compact, and efficient. Probably some type of chemical storage will have to be developed to fit these requirements.

The use of solar energy for water heating will most likely become more widespread as energy costs continue to climb. At present approximately \$75 a year could be used to construct and operate a solar water heater. If a standard unit could be designed which could be constructed of inexpensive materials available on all farms its acceptance might be fairly rapid in many areas.

Solar energy would be very adaptable to space heating if it were available every day of the year. Since it is not, energy storage units will be needed to supply energy for nights and cloudy days. Approximately $100 a year could be used for constructing and operating a solar energy space heating and storage system for home use. This is not a very large amount, but as different systems are built and tested there is a good possibility economical systems will be found.

At the present time no methods have been developed which make the conversion of solar energy to electricity practical for agricultural uses. The costs of fabricating solar collectors which need to cover a large area are prohibitive. Such collectors and energy converters can be used only for special installations at locations where conventional energy sources are difficult or costly to obtain.

PROPOSED FUTURE INVESTIGATIONS

1. Solar energy collectors and storage units for farm use should be further developed, fully tested, and plans made available for widespread use. The daily amount of energy received from the sun is many times the amount used from the conventional energy sources. The farm owner is ideally located to take the best advantage of this widely spread, low intensity, source of energy. It could be used for water heating, space heating, crop drying, and possibly several other purposes. The effort devoted to collecting and storing solar energy for agricultural production uses should be greatly increased.

2. An investigation should be made into the possibility of developing new methods of storing electricity for agricultural purposes. Electrical storage batteries are being extensively developed by industry sponsored research activities. Most of the emphasis has been placed on batteries for automotive and 'defense' uses. The agricultural producer could find many uses for a stationary storage battery. The battery would not have to be compact and space-conserving or built to withstand rugged use.

3. The possibility of using agricultural residues such as pulverized corncobs, sawdust, and other waste materials as a fuel for small gas turbines should be

investigated. It has been estimated that 10 to 20 per cent of the world energy is supplied by farm wastes. Although in the future it may be desirable to return most of the waste back to the soil, there are still some farm wastes which could be used as a source of energy.

4. The possibility of using plants to supply energy to an electrical circuit should be investigated. It has already been shown that a tree has an electrical potential. It should be determined if any plants have enough potential to cause a significant flow of electrons in a circuit.

5. The storage of hydrogen as an energy source for the fuel cell needs further study. Hydrogen has been shown to successfully operate the fuel cell. If the hydrogen fuel cell is to become commonplace new methods of storing hydrogen will need to be developed. It will have to be stored in a compact form and in such a manner that it is readily available and simple to regulate.

6. The storage of energy in chemicals is receiving much support by many private and public institutions and associations. Because of the widespread interest and activity in this area there will undoubtedly be beneficial results forthcoming in the next few years. The results of such work will have to be obtained by agricultural engineers and fitted to agricultural uses.

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APPENDIX

Table A-1. Wholesale prices and price indexes of selected individual commodities. Annual averages, 1958

Base period 1947-1949 = 100 unless otherwise indicated

		Wholesale price	Price index
Anthracite coal			136.6
Chestnut, Pa., Mine	Net ton	$14.239	125.0
Pea, Pa., Mine	Net ton	11.460	121.1
Buckwheat No. 1 Mine	Net ton	10.543	159.9
Buckwheat No. 3 Pa., Mine	Net ton	7.586	181.2
Bituminous coal			120.4
Domestic, large size	Net ton	7.70	121.8
Domestic, stoker	Net ton	7.20	125.0
Coke			161.9
Swedeland Pa., foundry by product	Net ton	29.500	159.1
Birmingham Pa., foundry by product	Net ton	28.850	184.4
Milwaukee, Wis., foundry by product	Net ton	30.500	157.8
Kearny, N. J., foundry by product	Net ton	29.75	152.1
New England, foundry by product	Net ton	31.55	151.9
Detroit, Mich., foundry by product	Net ton	30.50	163.2
Ironton, Ohio, foundry by product	Net ton	29.00	161.2
Indianapolis, Inc., foundry by product	Net ton	29.75	161.0
Gas, natural	1000 Mcf.	128.951	101.7
Gas propane, Houston	Gal.	0.047	
Gas propane, Okla., group 3	Gal.	0.046	
Electric power			100.4
Commercial	1500 Kwh.	52.205	(Jan., 1958)
Industrial	60,000 Kwh.	74.902	

Table A-1 (Cont.)

		Wholesale price	Price index
Gasoline			115.4
Gulf Coast	Gal.	$0.10	110.6
Oklahoma	Gal.	0.116	121.9
California	Gal.	0.115	104.8
Philadelphia	Gal.	0.145	100.0 (Jan., 1958)
Kerosene			117.7
New York Harbor	Gal.	0.103	114.0
Gulf Coast	Gal.	0.089	113.3
Oklahoma	Gal.	0.098	119.1
Distillate fuel oils			122.1
New York Harbor	Gal.	0.098	121.0
Gulf Coast	Gal.	0.085	123.9
Oklahoma	Gal.	0.087	117.4
California	Gal.	0.100	134.4
Residual fuel oil			111.7
New York Harbor	Bbl.	2.58	109.4
Gulf Coast	Bbl.	2.211	120.2
Oklahoma	Bbl.	1.333	82.2
Pacific Coast	Bbl.	2.388	136.9

From: United States Department of Labor (1959). Bureau of Labor Statistics. Wholesale Prices and Price Indexes 1958. Bulletin No. 1257. pp. 144-147. July.

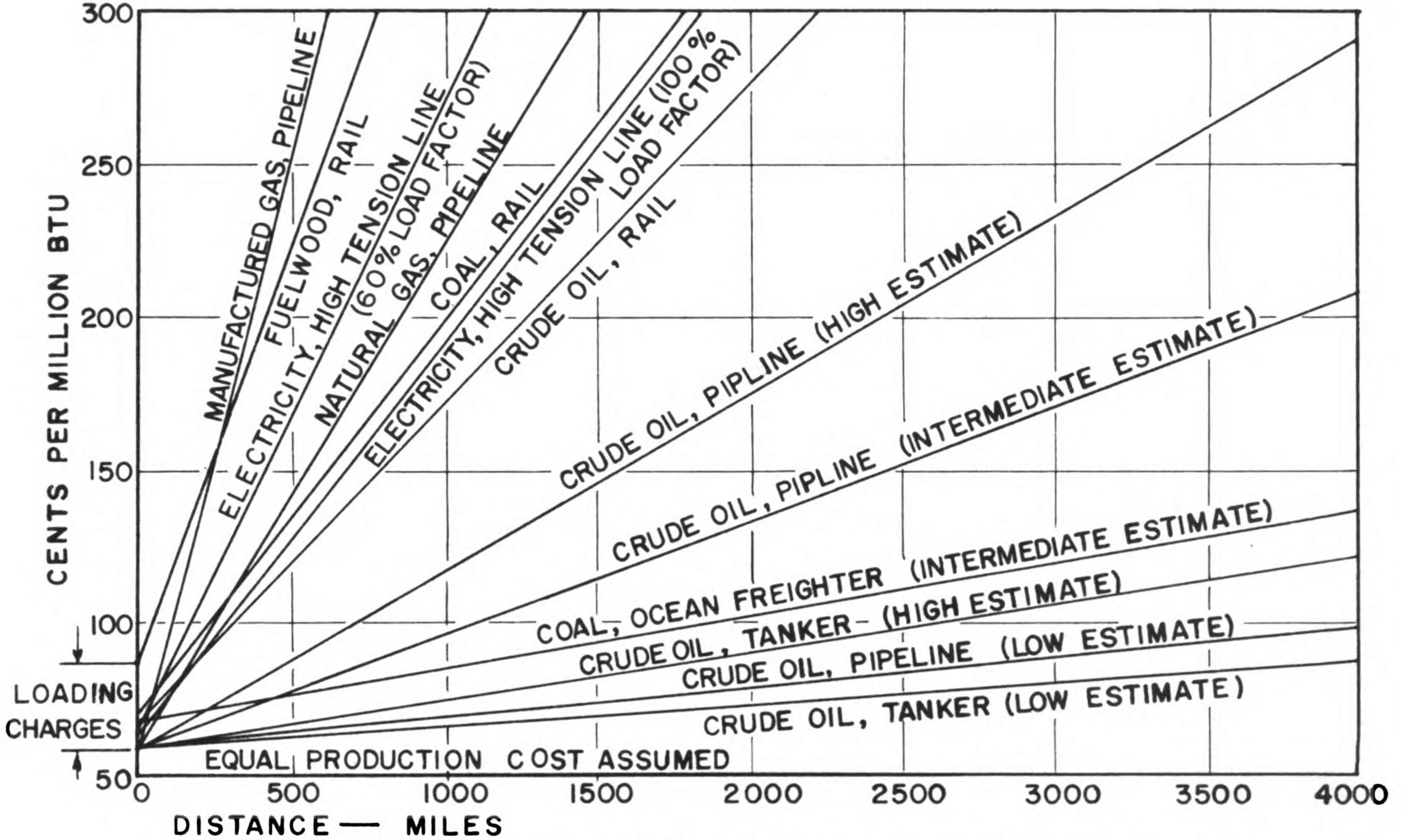
Table A-2. Wholesale price indexes, 1947-1958

Year	05 Fuel, power, and lighting materials	05-1 Coal	05-2 Coke	05-3 Gas	05-3 Gas fuels 1/58=100	05-4 Electricity	05-4 Electric power 1/58=100	05-5 Petroleum and products
1947	90.9	88.0	84.2	96.1	-	98.0	-	88.2
1948	107.1	106.2	104.3	102.4	-	99.2	-	111.7
1949	101.9	105.0	111.6	101.5	-	102.8	-	100.1
1950	103.0	106.2	116.1	98.2	-	100.1	-	103.7
1951	106.7	108.4	124.0	100.7	-	98.1	-	110.5
1952	106.6	108.7	124.7	103.7	-	98.9	-	109.3
1953	109.5	112.8	132.0	107.8	-	99.1	-	112.7
1954	108.1	106.3	132.5	108.8	-	101.8	-	110.8
1955	107.9	104.8	135.2	111.6	-	97.0	-	112.7
1956	111.2	114.5	149.7	115.1	-	94.2	-	118.2
1957	117.2	124.4	161.7	116.1	-	95.5	-	127.0
1958	112.7	122.9	161.9	-	101.7	-	100.4	117.7

Annual average indexes (1947-49 = 100) unless otherwise indicated

Key:
05-1 Coal--bituminous and Pennsylvania anthracite
05-2 Coke--foundry by product
05-3 Gas fuels--natural, utility, L.P.G., petroleum
05-4 Electric power--electricity to commercial consumers
05-5 Petroleum and products
Gasolene f.o.b. refinery or terminal
Kerosene f.o.b. refinery or terminal
Distillate fuel oil f.o.b. refinery or terminal
Residual fuel oil f.o.b. refinery or terminal

From: United States Department of Labor (1959) Bureau of Labor Statistics. Wholesale Prices and Price Indexes 1958. Bulletin No. 1257. July.



ADAPTED FROM "ENERGY RESOURCES OF THE WORLD", U.S. DEPT. OF STATE

FIGURE A-1. ENERGY TRANSPORTATION COSTS

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