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DUAL PURPOSE SOLAR-ELECTRIC POWER PLANTS

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Abstract

The rationale for such plants is discussed. The elements of such plants are listed. Some elements are discussed in more detail. Dual purpose solar-electric power plants would generate both electrical power and hydrogen gas for use as a fuel. The oxygen gas liberated in the hydrogen gas producing electrolytic cells would also be saved and sold to owners of hydrogen age equipment. Both gases would be under 50 atma pressure or more. At these pressures the hydrogen and oxygen could be fired in compressorless gas-turbine drives or fuel cell-invertor units of high thermal efficiency. The economics of dual purpose solar-electric power plants are weighed against costs of nuclear fission reactor-electric plants including the added value of the heated steam exhausted from gas-turbines and fuel cells. A recommended energy policy for America, first published in 1975, is attached.

Average Utility Operations

In order to establish how dual purpose solar-electric plants might fit into the US public utility picture we must look at the picture. Three hourly demands culled randomly from the literature are shown in Figure One. These are averaged in Figure Two where average demand is 48% of peak demand. This figure shows workday peaks exceeding those of weekends and holidays by a 7 to 5 ratio. The average case of Figure Two is reshuffled to present a demand versus % of time curve as shown in Figure Three. Average solar heat collection curves are superimposed in Figures Two and Three for the conditions of winter, spring, fall and summer.

Optimum Site for Solar-Electric Plants

This would be close to Yuma, Arizona, where clear insolation occurs 45% of the time, or 11 of 12 possible hours. This is the best insolation site within the continental USA and would be a likely location for the first competitive solar-electric plants. At Yuma the sun shines close to 3945 hours out of 8766 annual hours.

Time Adjustments

Two time adjustments are used to optimize use of solar-electric plants. The first is seasonal as follows:

(1) "Spring" = March, April, May
(2) "Summer" = June, July, August
(3) "Fall" = September, October, November
(4) "Winter" = December, January, February

The second is hourly with the sun at zenith at 1200 hours by standard time, but at 1400 hours by local time, so that 1800 hours peak demands will occur while sun is still above horizon.

Rationale for Dual Purpose Solar-Electric Plants

Storage of large blocks of electrical power as electricity is as of now impractical or too costly or both. Solar energy is a "free" fuel which is available less than half the time. Thus, solar-electric plants must collect energy at maximum possible levels whenever sun is shining without regard to momentary electrical demand. Collected solar energy should not be converted into electricity until needed to the extent that its subsequent release will cover two or three days of cloudiness. Beyond this practical limit of heat storage, all collected solar energy energy must be converted into electrical power or be lost. It follows that all such excess solar energy must be converted into hydrogen gas fuel using electrolytic cell-banks to insure its retention and efficient use. Since our demand for clean burning fuel gas exceeds our demand for electricity in terms of gross energy usage, it follows that dual purpose solar-electric plants should possess considerable excess capacity for hydrogen gas production on an interruptible basis.

Criteria for Dual Purpose Solar-Electric Plants

(1) Solar energy collectors should be of the weightless balloon type (A) to reduce cost of collectors to a reasonably small fraction of total plant cost and reduce collection tolerances.
(2) Solar energy collection should take place at maximum practical temperatures to assure the best thermal efficiency of conversion to electrical energy that is possible.

(3) Solar energy collector coolant should be a liquid metal alloy which will not freeze solid at ordinary nighttime temperatures, which can be very hot at very low fluid pressure, which has good heat exchange characteristics, low pumping power characteristics and which can be readily stored in tanks of reasonable size.

(4) Liquid metal heat exchange to boiler feed water heaters, boilers, superheaters and steam reheaters should take place in back-pressured platefin-type heat exchangers of stainless or super alloy materials to reduce cost of these exchangers to an irriducible minimum and eliminate necessity for extraction heating.

(5) Turbines should be standard except for no need for extraction heating which will reduce cost, complexity and will improve thermal efficiency.

(6) Generators should be standard.

(7) Condensers should be standard.

(8) Near Yuma, in dry country, ultimate heat rejection should be to cooling towers or to water drawn from more than 55 feet below the surface level of large reservoirs of water.

(9) Switchgear would have to be of the vacuum switch type to permit frequent on-off service which is inherently necessary in a solar-electric plant.

(10) AC/DC Rectifiers should be of the most modern high-efficiency solid state type to assure low cost DC current to electrolyzers.

(11) Hydrogen production cell-banks should be of the back-pressured type with low-cost electrodes built into pressure tanks to reduce cost of water dissociation to a reasonably small fraction of total plant cost (B).

(12) Off-gas oxygen should be saved and can be shipped from dual purpose solar-electric plants to load points either in separate 50 ATMA pressure lines or as LOX in tank trucks.

(13) Off-gas hydrogen should be contaminated to the extent of 1% impurities to (a) impart a smell to permit fast leak detection, (b) impart flame visibility to permit fast observation of flame conditions in burners and (c) preclude hydrogen embrittlement and failures of existing fuel gas transmission piping and gas holders.

(14) Off-gas hydrogen should be chilled, using neon refrigerators to low temperatures as necessary to insure proper BTU throughput through existing fuel gas transmission piping laid under several feet of earth cover which will suffice to permit transmission at 50 ATMA or higher for hundreds of miles with no need for pressure-boosting stations.

More Detailed Discussion of Critical Elements of Solar-Electric Plants

At the present time DOE has an extensive prototype program for development of the "power tower" concept for solar-electric power plants. Such plans would have collectors mounted on 1000-foot-high towers. Each tower would be to the south of or be surrounded by a field of gyrating parabolic mirrors, each mounted inside a bubble of water-clear water-resistant plastic film to obviate designing mirror supports to resist wind forces. Each mirror must be carefully aimed because tolerances for parabolic collectors are much tighter than for spherical collectors. Such plants are estimated to cost in the order of $2,500/KW or more. The hope appears to be to reduce the cost of reflective mirrors by one-third. If this hope proves out, the cost of "power-tower" solar-electric plants would approach from above the current cost of enriched fuel element fission reactor plants based on a realistic nuclear plant availability of 67% while neglecting publicly absorbed costs of enrichment or the totally unresolved problems of nuclear ash disposal. If critical elements of solar-electric plants are designed with least possible cost in mind, I believe such power plants can be far more cost effective. A discussion of these critical elements follows:

(1) Solar Energy Collectors

These would be of the weightless, tracking, concentrating, all-purpose solar energy collecting balloon type(A).Balloons can be either sperical or paraboloid in shape. A water-clear half of weather-resistant polyvinyl fluoride film, reinforced by a mesh of aramid yarn ropes covered by an opaque extrusion of weather-resistant plastic, would be continuously aimed at sun and permit almost all the light to pass into the balloon interior. Balloon halves away from sun would be a reinforced laminate of plastic film with the inner layer of water-clear polyester film with its exterior surface heavily aluminized followed by a layer of opaque white polyester film followed by a reinforcement mesh of aramid yarns followed by an opaque outer layer of weather-resistant polyvinyl fluoride film. Balloon fill gas would be air stripped at the site of oxygen using a small Stirling cycle cryogenic refrigerator. The buoyancy of nitrogen at 5" of water pressure will closely match balloon skin and tether weight. The light internal pressure will match the stagnancy pressure of winds at 100 MPH velocity. Balloons will be tethered to tracking mounts using aramid yarn ropes covered by an opaque extrusion of weather-resistant plastic arranged so that one-half of these go into tension whenever wind forces attempt to move a balloon from its proper position. Multitubed heat collection probes would be extended from tracking mounts along the solar oriented axis of balloon. Initially these would be cooled using a sodium-potassium alloy near the eutectic point which is liquid above 12^{O}F and meets all criteria listed previously. The metal of the tubing would be selected to withstand the collection temperatures of interest. Tubing would be arranged to provide a thermal insulation vacuum jacket between outer pass cool coolant and inner pass heated coolant. Outer surface of outer tube would have an annealed layer of copper oxide or equal so as to provide a selective heat collection surface and reduce re-emission losses. The ultimate hope would be to line the tubing with photo-voltaic cells to obtain direct conversion of solar energy into electricity. Whenever this may become technically and economically feasible the coolant could be water and the need for associated thermal-electric equipment would vanish. Thermal efficiency of electrical generation in solar-electric plants would be close to 43.5% in either case. Tracking mounts would be securely anchored to concrete bases sized to provide sufficient weight against wind uplift and anchored into soil so as to protect against displacement due to wind drag. Minimum base cost will occur when collectors are mounted atop north-south-oriented ridges so balloon bottoms can belly down into the valleys at dawn and at sunset. Balloon collectors are estimated to cost $5/# of balloon material, $3/Sq.Ft. of transverse cross-sectional solar light collection area and less than $1/Sq.Ft. of balloon surface area. It is likely that, as interest in this type of collector rises, better and better plastic film and yarns will be developed to extend useful service life. As of now this is estimated at 13 years plus or minus one year on the basis of embrittlement and failure due to sharp blows or cyclical flapping. Actually, balloon skin surface position should be very stable, and there is no vendor data as to the half-life of these materials used in this way.

(2) Coolant Subsystem
This would be very "standard" as liquid metal systems go. Piping and corrugated flexible hoses would be double piped. Inner tubes would carry heated and cool liquid metal. Annular space would be a vacuum jacket to provide thermal insulation and a drain for leaks when these occur. Storage tanks would be located at lowest level in steel-lined pits filled with crushed material to prevent spread of fire whenever pyrophoric material is lost. Circulating pumps would be vertical with inert gas over liquid metal surface pressurized to protect bearings and motor drives.

(3) Steam Generating Equipment
Conventional fossil-fuel-fired power plants require fuel handling, furnaces, water walls with excellent heat transfer characteristics, feed water heaters with good heat transfer characteristics and reheaters, superheaters and boiler convection passes, all having terrible heat transfer characteristics being limited on the flue gas side by an "h" factor of about 3 BTU/HR-Sq.Ft.-^{o}F. In solar-electric plants as described herein heat transfer characteristics of liquid metal to water or steam are all excellent and permit use of very compact back-pressurized platefin-type heat exchangers of relatively low cost, hung into steel-lined reinforced concrete vaults with ceramic fire brick liners to eliminate thermal losses. The entire assembly would probably fit inside the furnace box of a like capacity fossil-fuel-fired boiler unit which in turn needs flue gas to combustion air heaters of the regenerative type, flue gas particulate precipitators in many cases and a tall flue gas exhaust

stack. It is clear that solar-fired thermal electric plants can be much less costly in the area of steam generating equipment when compared to fossil-fuel-fired steam-electric plants.

(4) Vacuum Switches
The inherent on-off operation of generators powered from solar energy requires the use of vacuum switches so that arcs are broken in the vacuum rather than in air or oil. Vacuum switches can be recycled in position as often as a button can be pushed which is not true of other, earlier designs. While such switches are newer than competing types, they have demonstrated close to total reliability and are relatively inexpensive. Modern solar-electric plant switchgear of the vacuum arc breaking type will not be a major cost factor.

(5) AC/DC Rectifiers
DC current is needed to power electrolytic call-banks to dissociate water into its hydrogen and oxygen constituent gases. Dual-purpose solar power plant rectifiers should be of the modern, low cost, very efficient, solid state type of proven reliability.

(6) Hydrogen Production Cell-Banks
Inherently a KW-HR of electricity can be sold at a higher price than can its equivalent in raw fuel because it takes a high order of investment to generate power starting as often as not with the cost of raw fuel. It follows if hydrogen is to be our major fuel, conversion vehicle and storage medium that its derivation from electrical power must be based on use of energy that of itself is absolutely free, as is solar energy, and that the hydrolytic cell-banks must be of very high efficiency and very low cost. It should be noted that this is equally true for power plants having other "free" primary energy sources, such as geothermal heat, power from waterfalls, running rivers, tidal eagres or ocean currents and power from ocean temperature differentials or the wind. In any event, it is proposed that the common denominator, the hydrogen production cells, be of the electrolytic cells for producing hydrogen gas with low cost electrodes built into pressure tank

walls type(B). Electrodes would be of carbon steel close to 1/16". thick lined on both flat surfaces with a very thin veneer of stainless steel to protect the base metal from corrosion when electrolyte is alkaline, and allow in-cell current flow in either direction. Following Schmidt, 1899, each electrode would be bipolar to eliminate tons of copper. End plates would be of much thicker carbon steel plates also clad on each side with a thin veneer of stainless steel. Electrolyte would be of 15% strength NAOH or 25% strength KOH. The latter requires more pounds of reagent at a higher cost. In principle, KOH is more efficient as an electrolyte, but its attack on materials and exposed skin of workers is also much more virulent. Since a useful service life in terms of decades is a prime necessity, amortization of electrolyte cost is no problem since, in principle, it will remain in the cells and never need replenishment. As of now I would opt for 15% NAOH on basis of less initial cost and far less likelihood of in-cell material failure. The electrode plates would also double as in-cell pressure resisting diaphragms. The electrode plates must also be separated by dielectric separators and woven cloth separators to prevent untimely reunion of H_2 and O_2 molecules, while permitting ions in fluid to freely pass through membrane. Each half-cell must have an off-gas manifold sized and finned and filled with glass wool so as to condense out most of the water vapor and all electrolyte molecules. Obviously each cell must have its absolutely individualized and carefully measured water makeup controller to prevent short-circuiting. There may be many ways to go, but the joining of FEP, truly thermoplastic, Teflon to stainless surfaces using the hot melt procedure shows the most promise to date. This allows the FEP Teflon to bridge the gap over short distances (cell pitch = 1" or less) at structural stresses which are easily within its material capabilities. End plates would be back-pressured using essentially the same detail as would be used to restrain in-cell pressures. This will permit low cost cell-banks to be operated at just above fuel gas transmission pipe line pressure at close to 800 PSIA, and eliminate the need for hydrogen pipe line compressors.

(7) Hydrogen Chillers

An economical way to insure adequate flow through existing fuel gas transmission piping is to chill hydrogen below ambient temperatures. Neon at cryogenic temperatures is an ideal refrigerant with enormous heat removal capacity. Hydrogen contains three times the heat content per pound found in petrofuels, and four times that of the best grades of coal. It is also very fluffy so that a standard cubic foot of hydrogen contains only a third of the heat content of a standard cubic foot of natural gas. Most existing gas transmission pipes are buried under many feet of dirt which can be used to provide thermal insulation and will allow low cost chilling of hydrogen to improve heat content throughput. Neon compressors would be of the screw-machine type which are suitable for continuous duty under variable loading. Maximum possible chilling using neon refrigerators would be to about $60^{\circ}R$ for a reduction in hydrogen specific volume by a factor of nine.

Dual-Purpose Solar Plant Costs

For simplicity a dual purpose solar power plant is assume to have half of its capacity dedicated to electrical power generation during sunlit hours and storage of hot liquid metal for continued generation when sun is not shining. Any excess electricity would be used to dissociate water. The other half of plant capacity would be dedicated to production of hydrogen (and oxygen) during sunlit hours, with no provision for storing hot liquid metal. A block diagram for such a plant is shown in Figure Four.

Dual-purpose solar power plant output would consist of electricity transmitted to load points using high tension transmission lines and hydrogen and oxygen gases transmitted to load points using fuel gas transmission pipe lines in the case of hydrogen and LOX tank trucks in the case of oxygen. Ultimately the hydrogen and oxygen would be fired in H_2-O_2 fuel cell-inverter units belonging to either the utility system or its customers. The fuel cell units are not limited by Rankine cycle limitations, and can generate electrical power at a thermal efficiency of up to 80%. The remaining heat value leaves these units in its low pressure steam effluent which in turn can be used for heating and cooling of buildings or vehicles. Dual supplies of hydrogen and oxygen are potentially of far more value than hydrogen or any other gas (or liquid) fuel furnished separately. A block diagram of a dual-purpose solar power plant utility system sales is shown in Figure Six.

Annual production costs for dual-purpose solar plants are taken for 25 years with interest at 9%, operation and maintenance at 2½% and linear payback at 4%. Total annual production costs are then 9/2 plus 2½ plus 4 or 11%.

Estimates of capital costs are for 1977 USD and include a 100% surcharge for existing transmission and distribution systems. Annual production costs are increased 10% to cover customer accounting and administration. Unit prices to customers are projected to equal those which are likely to be in effect in the United States in 1982(C).

Estimated Capital Costs:	
Collectors, 1745 @ 284,188	$ 496,000,000
NAK Systems, 7,356,000 x 30	221,000,000
Boilers 3,200,000 x 100	320,000,000
T-G, C. SGR 3,200,000 x 100	320,000,000
Cooling Towers 4,196,000 x 20	83,000,000
Rectifiers 2,200,000 x 30	66,000,000
H_2 Cell Banks 2,200,000 x 40	88,000,000
EACM, land 10% of above	156,000,000
	$1,750,000,000
Transmission, Distribution, Other	1,750,000,000
	$3,500,000,000
Annual Production Cost @ 11%	$ 385,000,000
Add for Customer Accounting & Administration	38,000,000
	$ 423,000,000
Annual Sales:	
Electricity 12,300,000 MBTU @ 15	$ 184,000,000
H_2 and O_2 29,120,000 MBTU @ 10	291,000,000
	$ 475,000,000

Profit & Taxes = 100(475-423)/423 = 12.3%

Unit Prices: $184,000,000/3,610,000,000 KW-HR = $0.051
$291,000,000/8,532,000,000 KW-HR = 0.034

It is concluded that dual-purpose solar power plants of the type described above can be very competitive and in just a few short years.

Hydrogen Age Equipment

If we decide to produce hydrogen and oxygen on a national basis there will be tremendous impetus to refine designs and mass produce fuel cell-inverter units of every size. Since these units are modular all of them will be equally efficient. The wide use of these units for powering public and private transportation vehicles would be of tremendous benefit in and near our crowded cities. Fuel consumption would be minimal and only effluent would be water vapor.

The tremendous investment in steam turbine-driven generator sets owned by public utilities and industry can continue to be of service. The steam turbines could be converted to Aphodid cycle service(D), with condensate recycled through a hydrogen-oxygen burner mounted at the turbine steam inlet. The condensate is recycled to keep hot end turbine wheel and casing temperatures at acceptable levels while an amount of condensate equal to the mass flow of hydrogen and oxygen must be continuously removed from the system. If the amount removed is taken from a low pressure section of the turbine casing it could then be sold locally for space heating, space cooling using absorption type water chillers and to restaurants for warming counters and washing dishes. Thermal efficiencies for such equipment would be higher than before and steam sold would increase revenues.

Since America is the largest user of energy obtained mainly by the depletion of non-replenishable fuels, it makes sense that the conversion of the world to a gaseous-hydrogen-fuel-based economy start here. If it is to be done well it is important that we in America face up to the task and adopt a comprehensive energy program toward that end. As of now America does not have such a policy. In the interest of helping obtain a national consensus on what we should do to assure ourselves and our successors complete success in meeting future energy requirements, I have appended a copy of "A Proposed Comprehensive Energy Program for America" which I first published in 1975 and which was also appended to References(A) and (B).

References

A. "Solar, Geothermal, Hydrogen & Hydraulic Power," presented by Frederick F. Hall at the American Society of Civil Engineers Spring Convention held in Dallas, Texas in April 1977.

B. "Hydrogen Production Plants Using Electrolytic Cells With Low Cost Electrodes Built into Pressure Tanks," presented by Frederick F. Hall at the First World Hydrogen Energy Conference sponsored by ERDA and the University of Miami held in Miami Beach, Florida in March 1976.

C. B.L.S. Consumer Price Index and Price of Electricity as published in the General Electric pocket size "Technical Data," booklet, 1977 issue.

D. "A Proposed Hydrogen-Oxygen Power Cycle," by Stanley O. Brauser, School of Mechanical Engineering, Oklahoma State University, and William L. Hughes, Head, School of Electrical Engineering, Oklahoma State University, Stillwater, Oklahoma.

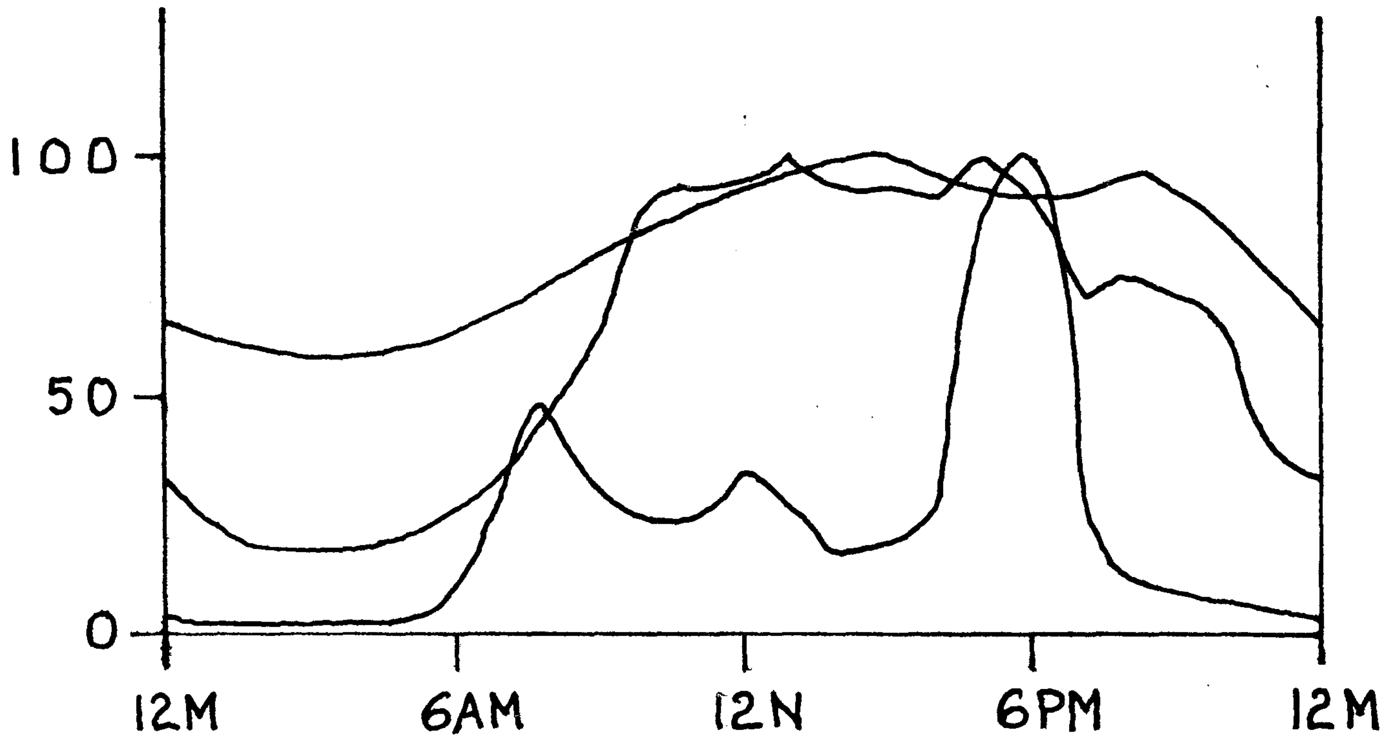

FIG. 1

% DEMAND VS. TIME - THREE SYSTEMS

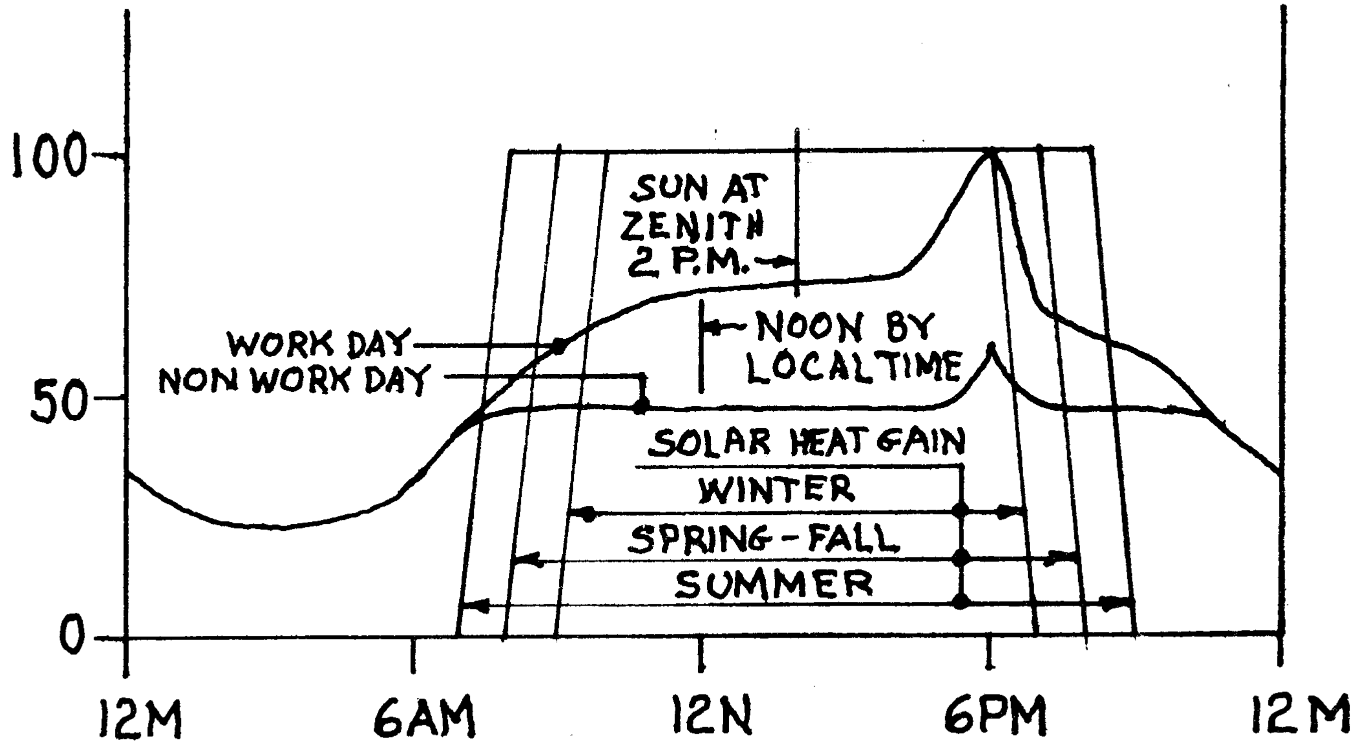

FIG. 2

AVERAGE DEMAND AND INSOLATION VS. TIME

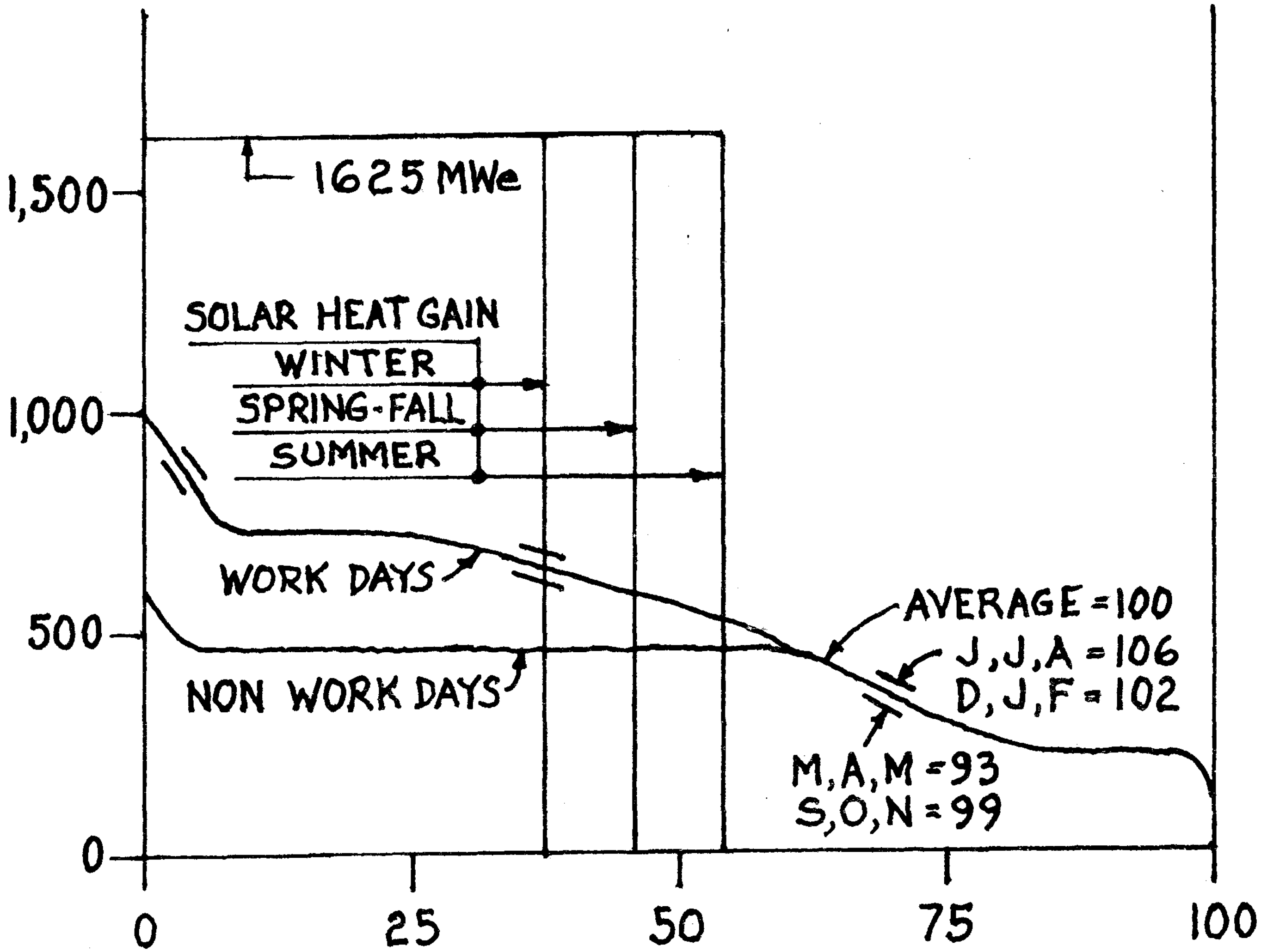

FIG. 3

MW DEMAND AND SOLAR MWe VS. % OF TIME

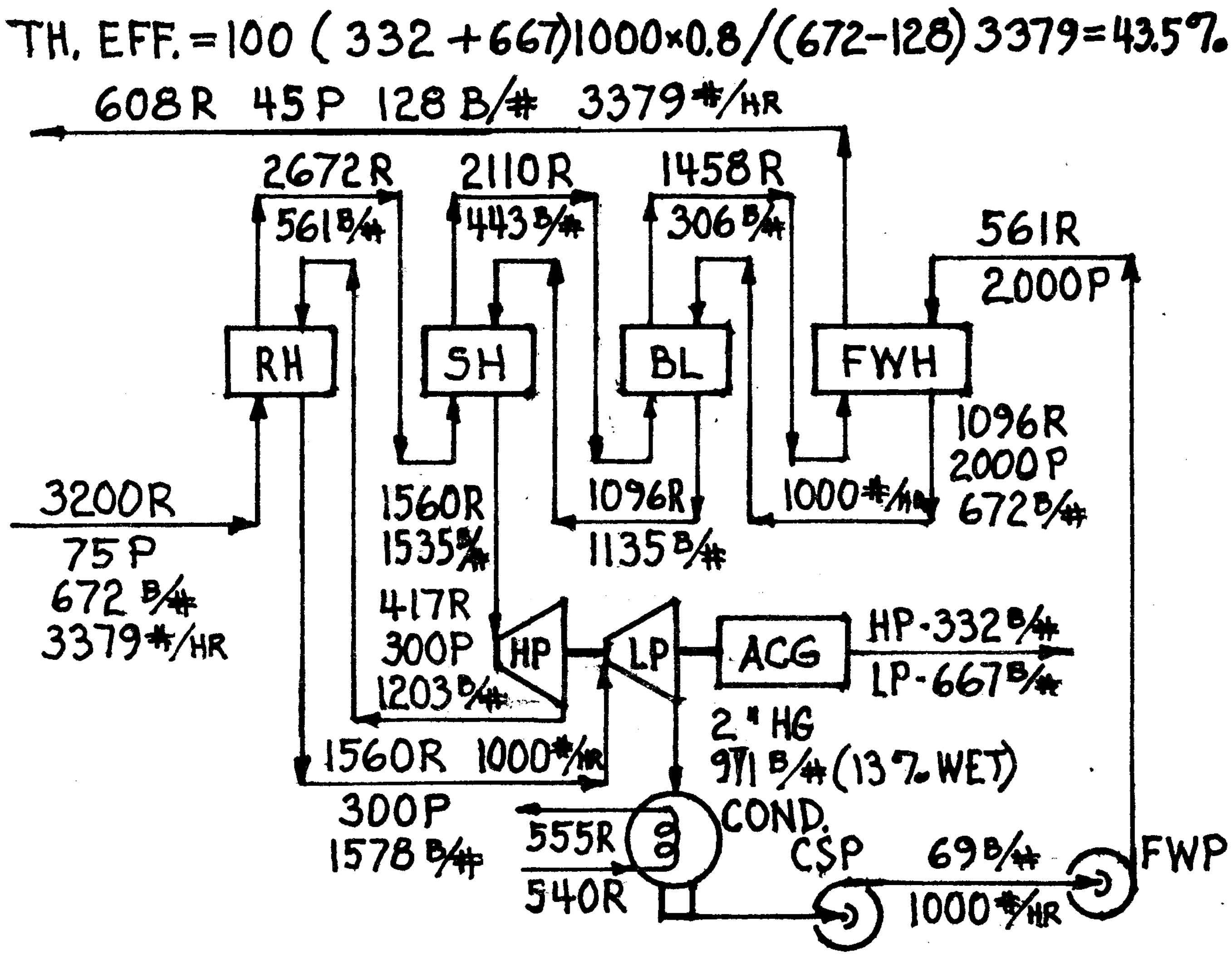

FIG. 4
SOLAR PLANT STEAM-ELECTRIC HEAT BALANCE

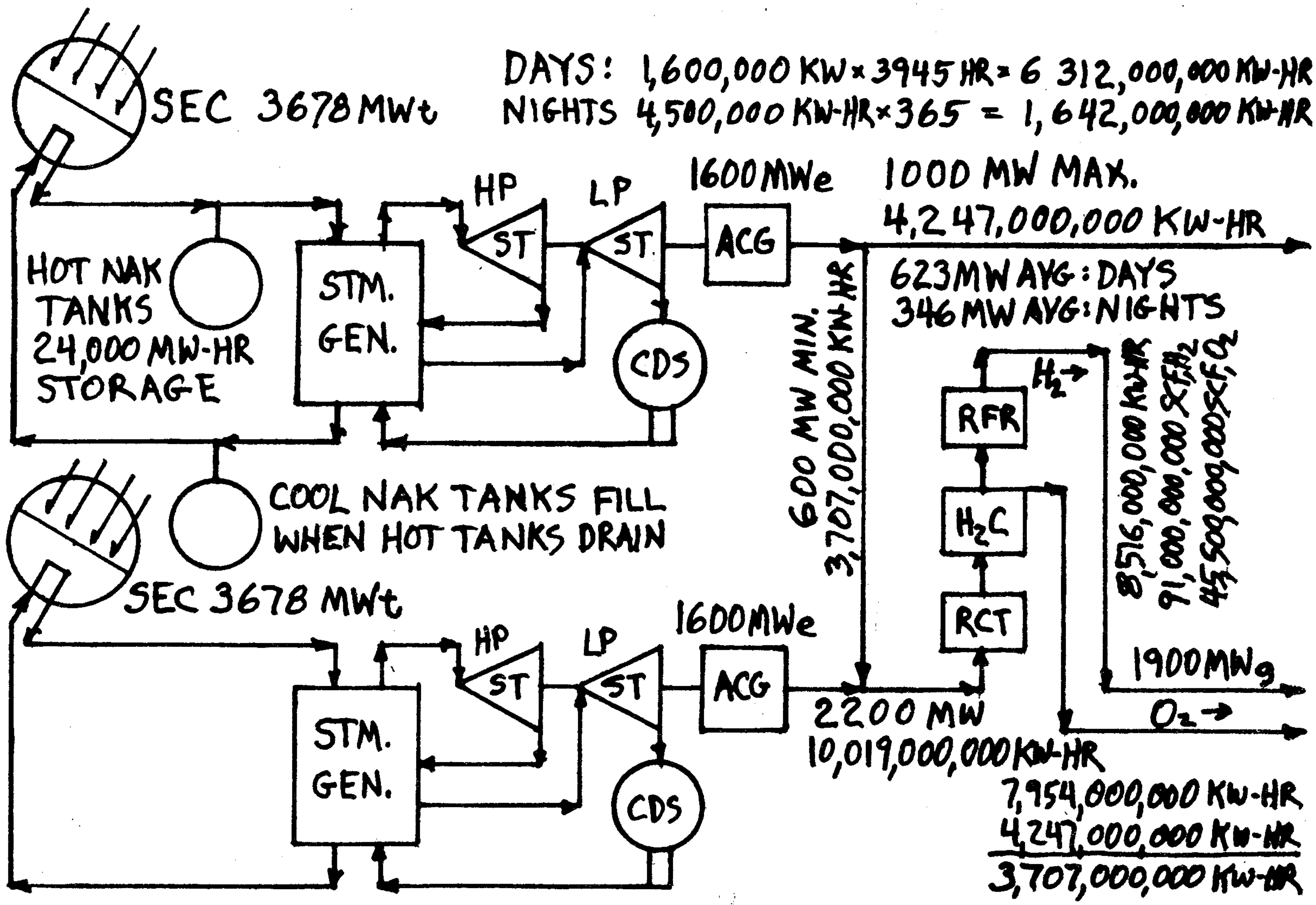

FIG. 5

DUAL PURPOSE SOLAR PLANT BLOCK DIAGRAM

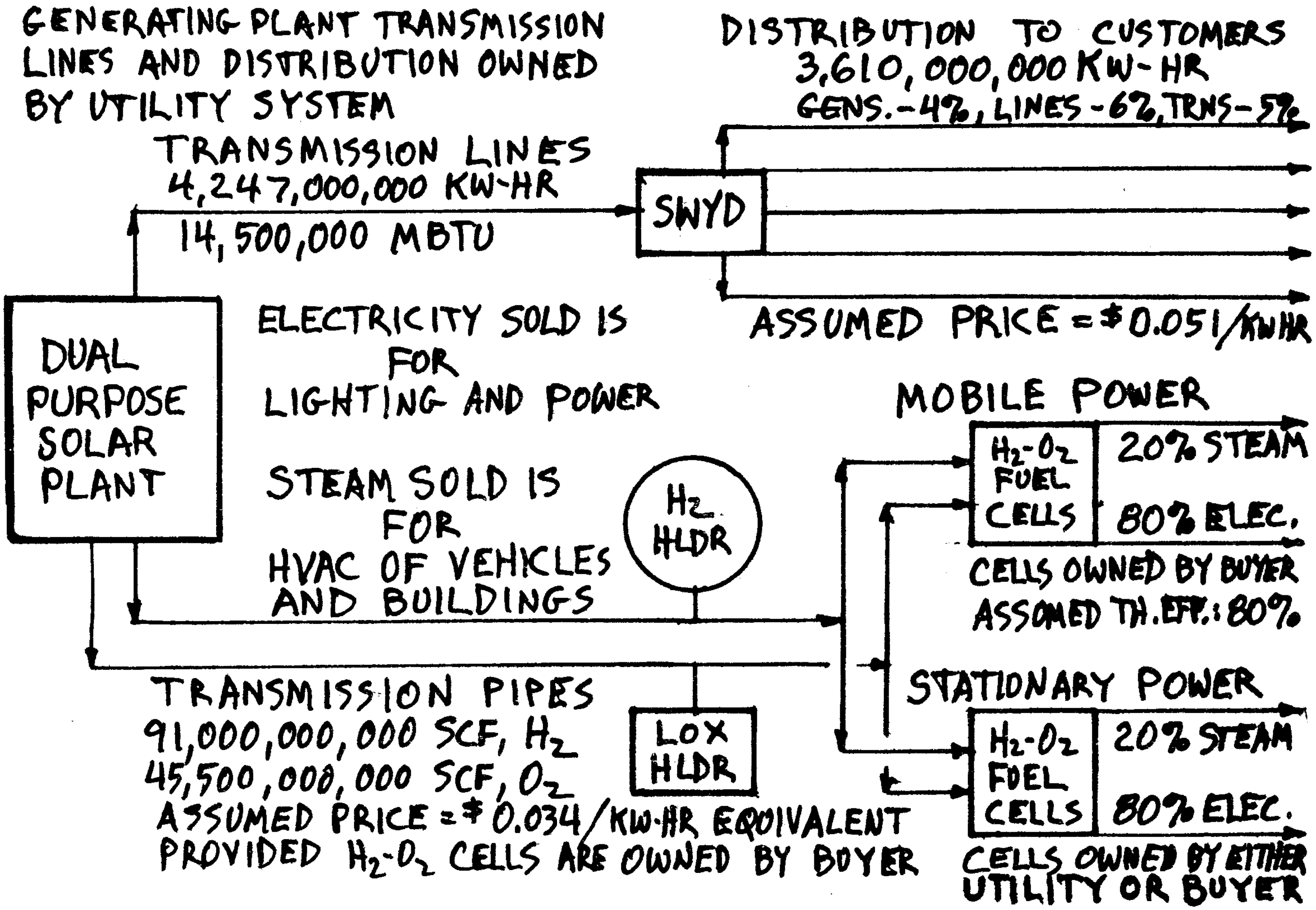

FIG. 6

DUAL PURPOSE SOLAR PLANT SALES OF KW-HR, H_2 & STEAM