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Electric Power Required in the World by 2050 for Electric Power and Hydrogen Fuel

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Abstract

Nuclear energy will be required in much larger quantity as worldwide demand for electrification and substitution of hydrogen for fossil fuel in transportation will grow over the next 50 years. Meeting the total future demand for electricity and hydrogen fuel as parallel energy carriers raises the question of the sustainability of primary energy supply, even with widespread acceptance of nuclear energy as a large-scale energy resource. Forecasts for electricity demand over the next 30 years show a mean annual growth rate ranging from 1.7% to 3.4%, which when extrapolated from the present annual consumption of 16 PWh* in 2002 to the year 2050 suggests an electricity demand in the range of 36 to 82 PWh. In addition to this business-as-usual growth in demand, estimation of the growth of the world automotive vehicle fleet from about 900 million vehicles in 2010, consuming about 360 billion gallons of petrol, to about 1500 million vehicles in 2050, which could be operated with about 260 billion kg of hydrogen fuel, would result in additional electricity demand of about 10 PWh annually for replacement of fossil fuels in transportation. With approximately 175 PW of solar power reaching earth and world fossil fuel reserves of 50-200 years remaining at present consumption rates, the question arises of how much of the world's future electric energy supply will be required (if any) from nuclear fuels.

Introduction

Substitution of hydrogen for fossil fuels for vehicle transportation over the next 50 years will require development of large-scale hydrogen production by electrolytic (or other) means as mass production of fuel-cell engines accelerates. As the concomitant growth of electricity demand increases, the need for additional electric power capacity will also accelerate. For the potential size of the world vehicle fleet by 2050, large-scale electrolysis (or high-temperature thermochemical decomposition) of water may become the primary means to produce hydrogen fuel in sufficient quantity.

∗ peta=10^{15}

Utilization of hydrogen as an automotive fuel is encouraged by two strong driving forces in the world: (1) substitution of increasingly scarce and costly fossil fuels; and (2) abatement of global air pollution. Unlike petroleum production, which is concentrated in only a few well-endowed countries, electrolytic production of hydrogen is possible in all countries as an indigenous supply of transportation fuel. Abatement of air pollution includes reduction in vehicle exhaust of both carbon dioxide (and other greenhouse gases) to the global environment and smog-forming nitrogen oxides in metropolitan air basins.

The commercial viability of hydrogen as a transportation fuel requires reduction in the unit cost of hydrogen fuel to meet the increasing unit cost of fossil fuels as they become more expensive. The anticipated growth in population and vehicle fleets throughout the world makes the introduction of hydrogen fuel more desirable and will require rapid growth of a hydrogen fuel industry with rapid production to very large quantities. Although many methods of hydrogen production are under study, electrolysis of water (and perhaps high-temperature thermochemical decomposition of water) is likely to become the primary means of hydrogen production in sufficient quantity to meet the future fuel demand for the world's vehicle fleet, which is expected to reach about 1.5 billion vehicles for a population of more than 9 billion by 2050. These expectations would result in a growth in world affluence from 0.113 vehicles per capita in 2000 to about 0.16 vehicles per capita in 2050.

The problem of energy supply for a new transportation fuel cannot be separated from the larger problem of energy supply for a growing world population, especially as new demands are made on the electricity supply for new high energy-intensive applications, such as computers, mobile cell phones, information technology, home management, superconductor grids, aviation security, and homeland defence. Another major concern about the need to curtail use of fossil fuels, especially natural gas which is perceived as a 'green' fossil fuel for residential energy supply, is the need to balance the competition for oil and natural gas between chemical use as a raw material and combustion use for thermal energy production.

The future sustainability of energy supply with introduction of a new large industry to produce a new transportation fuel is dependent on both the growth of world population and the affluence growth in vehicle ownership. This problem was examined by Kruger (2001) in estimating the energy requirement for rapid growth of a hydrogen fuel cell vehicle industry over the next 50 years to replace production of fossil fuel internal combustion engine vehicles by the major automobile manufacturers of the world. The estimates were prepared with a dynamic model which incorporates historic and forecast growth data obtained from pertinent government agencies. With the rapidly changing conditions in global economy, collation of more recent data than used in the prior model suggested a revision of the estimates, which are presented here.

The model covers two time periods: (1) from 2000 to 2010, when fuel cell vehicle production is initiated with rapid expansion; and (2) from 2010 to 2050, when a significant fraction of the world fleet could be operating with hydrogen fuel. The output of the model provides an estimate of the potential size of the vehicle fleet, the hydrogen fuel demand for its operation, the additional electric energy requirement to produce the fuel by continuous improvement in large-scale electrolysis of water, and the additional installed electric power capacity to meet the electric energy load in addition to the growth of electric energy demand under business-as-usual conditions (i.e. without a fuel cell vehicle industry or any other new energy intensity industry). This study concludes with an estimate of how the total energy demand can be met by continued reliance on fossil fuels, growth of renewable energy use, and accelerated growth of nuclear power capacity for both large-scale electricity generation and production of hydrogen fuel by electrolysis (and possibly high-temperature thermochemical dissociation) of water.

The HFleet Electric Energy Demand Model

The hydrogen fuel-electric energy model was developed as a two-step dynamic model with the Stella-II program (Hannon and Ruth, 1994). Details of the model were described by Kruger (2000, 2001). This report updates the 2001 study for the world vehicle fleet in that several improvements were made in obtaining and collating additional travel data for the world. The updated model was numerically verified with the Matlab program (Hahn, 2002). The first step uses population data (UN, 2003) and improved vehicle data (IRF, 2002) from 1980 through 2002 to extrapolate the size of the world vehicle fleet to 2010 on the basis of a steady but saturating growth in vehicles per capita. The many types of vehicles with large variations in annual travel distance and fuel economy were grouped into two general types: light (automobiles, vans, and SUVs) and heavy (buses and trucks) vehicles. These data were used to estimate for 2010 the number of vehicles of each type, the mean annual travel distance, and the mean fuel economy (U.S. EPA, 2003) to calculate the fuel (as gasoline) requirement. The electricity data (UN, 2002 and DOE/EIA, 2003) were similarly extrapolated to 2010 to estimate the electric energy demand under business-as-usual (B.a.U.) conditions and the installed capacity of electric power.

The second step of the model examined a range of fuel cell vehicle growth rates over the next 40 years from 2010 to 2050. In this step, the fuel demand is converted from gasoline to kilograms of energy-equivalent hydrogen. The annual electric energy consumption for producing hydrogen by today's electrolysis equipment using 50 kWh/kg was calculated with linear improvement by higher-temperature technology to achieve a value of about 40 kWh/kg by 2050. In addition to the extrapolated data from the first step, input values included a range of initial annual production growth rates for fuel cell vehicles from 20% per year, which would contribute a very small contribution to the future vehicle fleet, to 40% per year, which would result essentially in complete replacement of the fossil fuel fleet with hydrogen fuel by 2050. For the results reported here, the model used constant mean annual travel distances (in trillion vehicle kilometers travel, TVKT) and fuel economy (in km/kg) from literature estimates. The electric energy requirement was added to the business-as-usual electric energy demand and the total installed capacity to meet the total demand was calculated.

Extrapolation of 1990-2000 data to 2010

Table 1 summarizes the data for the initial conditions in 2000 and the mean annual growth rates (m.a.g.r.) as the input parameters of the model and the output results for 2010. The results are compared with those in the prior (Kruger, 2001) study. The extrapolated values for 2010 show several significant differences from the prior study values, which were based on data from 1980 through 1995. This is especially pronounced in the vehicle data in which the many types of vehicles were grouped differently between light and heavy vehicles. The fleet size values show an 11% decrease over the 5-year change in data. The most significant difference occurred in classification of vans, such as pickups and SUVs, which were included in heavy vehicles earlier and light (2-axle) vehicles in this study. The difference carried over into annual vehicle miles of travel and mean fuel economy. However, the very large change in gasoline fuel consumption resulted from the very large growth rate of heavy vehicle travel from the sparse earlier data. The extrapolated electricity values increased only a few percent over the 5-year period reflecting an increasing demand for electric energy.

Table 1
Input Parameters (2000) and Extrapolations (2010)

Parameter (Units)	Initial Value (2000)	m.a.g.r. (%/year)	Prior* Value (2010)	Current Value (2010)
Population (10^9)	6.06	1.30	6.94	6.89
Ownership (VpC)				
• Light Vehicles	0.079; max: 0.10	& 0.62	0.10	0.078
• Heavy Vehicles	0.034; max: 0.06	2.99	0.05	0.038
• Fleet	0.113		0.15	0.116
Fleet Size (10^6)				
• Light Vehicles	478	1.16	555	537
• Heavy Vehicles	206	2.48	347	264
• Fleet	684		902	801
Travel Distance (10^{12} VKT)				
• Light Vehicles	7.38	0.57	8.08	7.81
• Heavy Vehicles	1.78	1.30		2.03
• Fleet	9.16		10.25	9.84

continued…

Parameter (Units)	Initial Value (2000)	m.a.g.r. (%/year)	Prior* Value (2010)	Current Value (2010)
Fuel Economy (km/U.S.gal)				
• Light Vehicles	38.8	& 0.34		37.5
• Heavy Vehicles	11.8	1.16		13.3
• Fleet				32.5
Fuel Consumption				
• Gasoline (10^9 gal)			825	361
Electricity				
• Energy Demand (PWh)	15.35	2.76	19.27	20.23
• Installed Capacity (TW)	3.40	2.09	4.04	4.19

* Kruger (2001)

Requirement for hydrogen and electricity 2010 to 2050

The potential growth of a hydrogen fuel cell vehicle industry in the world is as yet uncertain. Many automobile manufacturers have endorsed the concept of replacing the internal combustion engine with fuel cells and many oil companies have initiated hydrogen fuel subsidiaries. But the infrastructure for solving the "chicken or egg" dilemma of when there are enough fuel cell vehicles on the road to warrant widespread construction of hydrogen refuelling stations and when there is enough distributed hydrogen fuel to warrant mass production of fuel-cell vehicles remains to be developed. But the real problem, as noted in this study, is the long (15-20 year) lead time needed for exponential growth of both the number of 'chickens and eggs' from initial small numbers to make a meaningful impact on the fossil fuel problem. Since the lead time is reasonably fixed, the longer it takes to start the new industry, the longer the time to reach significant impact.

The major choices in modelling a 40-year growth of a new industry are (a) when to start, (b) the initial production values, and (c) the expected growth rates. The choice for (a) was fixed at 2010 before which time the driving forces of fossil fuel supply and global warming concerns are likely to overcome the barrier of hesitancy. The choice for (b) was selected as an initial production in 2010 of 10 000 each of light and heavy vehicles. The light duty vehicles would most likely be centrally refuelled fleets of automobiles and light delivery vans and the heavy duty vehicles would most likely be buses (and trucks) shown from the existing demonstration projects to be well suited for mass transportation in congested urban cities. The choice for the key parameter (c), the growth rate of hydrogen fuel cell vehicle production, was selected to cover the range from unimportant (20% per year), moderately important (30% per year), to fully successful (40% per year). The revised model, not in the earlier study, incorporates a logistic curve limit to the growth rate of the hydrogen fuel cell fleet (HFleet) as it tries to catch up asymptotically to the conventional (I.C.E.) fleet due to expected closure of I.C.E. vehicle production facilities near the inflection point time of the growth period. The result of this revision is a somewhat smaller world HFleet, reduced consumption of hydrogen fuel, and a smaller additional electric energy requirement.

Figure 1 shows the results of the model study in which the world vehicle fleet grows initially at the historic growth rates (1.16% per year for light vehicles and 2.48% per year for heavy vehicles) and reaches a size of 1.4 billion vehicles by 2050 which would continue to grow with its then current mean annual growth rate. *Figure 2* shows the corresponding hydrogen fuel requirement, which could be satisfied for the 20% per year growth rate by existing commercial hydrogen production facilities, but would exceed 260 billion kilograms per year at total fleet replacement by 2050 at a m.a.g.r. of 40% per year. *Figure 3* shows the resulting range of electric energy demand relative to the business-as-usual growth in demand. The business-as-usual growth at 2.7% per year would be sufficient to satisfy the energy need for the 20% per year growth rate of the Hfleet. Replacement of the conventional fleet would require an additional 10 PWh per year. *Figure 4* shows the corresponding range of electric power capacity required to supply the electric energy load. The business-as-usual growth in capacity would be sufficient to produce hydrogen fuel demand growth at 20% per year at 9.6 TW, but the total capacity needed for HFleet replacement would increase to 10.9 TW. *Table 2* summarizes the model output results.

Table 2
Summary of the Output Data: 2010 to 2050

Year	M.a.g.r. (%/a)	Hfleet (10^6 veh)	Hfuel (10^9 kg)	ElecEn (PWh)	SysCap (TW)
2010	B	0.02	0.00	0.00	0.00
	WVF*	801	B	20.23	4.19
2020	20	0.12	0.02	0.00	0.00
	30	0.28	0.05	0.00	0.00
	40	0.58	0.11	0.01	0.00
	WVF*	937	B	26.56	5.15
2030	20	0.77	0.14	0.01	0.00
	30	3.79	0.71	0.03	0.00
	40	16.5	3.09	0.14	0.02
	WVF*	1096	B	34.87	6.34
2040	20	4.73	0.88	0.04	0.00
	30	50.7	50.7	0.39	0.05
	40	373	69.7	2.91	0.39
	WVF*	1282	B	45.78	7.79
2050	20	28.9	5.39	0.21	0.03
	30	511	95.4	3.72	0.50
	40	1390	259	10.10	1.35
	WVF*	1500	B	60.11	9.58

* Forecast of world vehicle fleet (WVF) size without hydrogen fuel-cell vehicles.

A model study was also made of the dependence of the world hydrogen fuel fleet size as a function of a larger initial number of light and heavy hydrogen fuel-cell vehicles produced in 2010 at a m.a.g.r. of 40% per year. The results showed two notable characteristics compared to the results for the 20 000 vehicles in Table 2. The first was a more rapid replacement, as expected, of the conventional fleet by fuel-cell vehicles before 2050. The second characteristic, which was less obvious but is more important, is that for any initial value that is small compared to the size of the conventional fleet, even at m.a.g.r. of 40% per year, the time for exponential growth to a significant fraction of the fleet will have a lag time of at least 15-20 years from 2010, which would put the dates well past the maximum forecast period of 10-25 years by most government agencies.

Discussion

The key unknowns in evaluating the adequacy of the world's electric power capacity that will be needed by 2050, with or without a hydrogen fuel industry, are (1) the actual growth rate of electrical energy consumption over the next 50 years and (2) the future role of nuclear energy in maintaining the growth of the world economy. Forecasts by the U.S. DOE/EIA (2004) assume a future growth rate for world electric energy through 2025 of 2.3% per year, compared to the historic growth of 2.8% per year in the last 10 years. The difference between these two growth rates represents a 28% increase above 41.0 PWh (at 2.3% per year) to 52.4 PWh (at 2.8% per year) in 2050. With expectation of new and unplanned world demand for electronic services, aviation security, homeland defence, and other high-intensity electric energy applications, the assumption by the U.S. Department of Energy that no new nuclear power plants will come on line by 2025 hinders the needed long-term planning for an adequate electricity supply in the second quarter of the 21st century. The forecast through 2030 by the International Atomic Energy Agency (IAEA, 2003) for electric energy and the fractional role of nuclear energy in the world shows a more uncertain picture with forecast modelling of low and high estimates based on actual data for 2002 and a range of assumptions about the future. The low and high m.a.g.r. for total electricity consumption is 1.7% and 3.4% per year, whereas for nuclear energy it is 0.4% and 1.9% per year, also indicating a diminishing role for nuclear energy. Thus, the question remains: "Where will the additional energy required to change from fossil-fuel transportation to hydrogen fuel-cell transportation come from?" The total world energy consumption must come from some combination of fossil fuels, renewable energy resources, and nuclear energy.

Table 3 examines the potential distribution of energy resources available for hydrogen production and the range of fossil and nuclear energy supply needed to meet the total energy requirement, even on the possibility that electricity generation by renewable resources could meet 50% of the requirement by the year 2050.

Table 3
Potential Distribution of Energy Resources for Hydrogen Fuel Production in the World

Year	Forecast IAEA* (PWh)	Demand Model (PWh)	Forecast Renewables# (PWh)	(%)	Fossil Fuels (PWh)	(%)	On-line Nuclear* (PWh)	(%)
2002	16.1	16.2	2.89	(19)	9.9	(64)	2.57	(16)
2010	19.9	20.2	3.69	(18)	13.4	(66)	3.10	(15)
2020	27.9	26.6	4.62	(17)	17.9	(68)	4.01	(14)
2030	39.0	34.9	5.80	(17)	25.1	(72)	3.98	(10)
m.a.g.r. (%/a)	3.4	2.8	2.3	(-0.4)	2.2	(0.4)	1.6	(-1.2)
2050	n/a	70**	35	(50)	X		Y	

Range of Distributions for U.S. Energy Supply with HFuel

X	(%)	+	Y	(%)	No.NPP
35.0	(50)		0.0	(0)	0
17.5	(25)		17.5	(25)	1750
0.0	(0)		35.0	(50)	3500

* source: IAEA, 2003
\# source: EIA, 2002
** total demand = 60.1 PWh (w/o H_2 production) + 10.1 PWh (w/ H_2)

The Table compares forecast demand through 2030 by IAEA (2003) High Estimate Case with the model results. It shows the rapidly growing deficit by the assumption of a 3.4% per year growth rate compared to the historic growth rate of 2.8% per year. The Table shows the fraction of electric energy from renewable resources (mainly hydroelectric energy) declining from 19% to 15% at a rate of 0.4% per year, and the negative growth in nuclear energy declining from 16% to 10% by 2030 at a rate of 1.2% per year. The Table shows the model's estimate of total electric energy demand by 2050 reaching 70.2 PWh, consisting of 60.1 PWh from business-as-usual growth (including growth in the electronic age) and 10.1 PWh required to produce about 260 billion kilograms of hydrogen fuel per year for the fuel-cell vehicle fleet. On the very uncertain assumption that 50% of the total electricity demand could be met with renewable energy resources, without large growth of additional hydroelectric power installations, the remaining 50% must be obtained from some combination of fossil and nuclear energy.

The second part of the Table illustrates the range of distributions for these two energy resources, from all fossil fuel to all nuclear fuel. Long-term planning must consider such issues as the public's desire for a clean environment and renewable energy sources, the rapid expansion of long-term commitment of natural gas combustion for electric power capacity additions, the need for conserving natural gas for chemical feedstock and residential heating, and the additional electric power needed for the newly created electricity demands, including a new hydrogen fuel industry that cannot become significant until after 2030, the period beyond current government planning.

The world now has more than 440 operating nuclear power plants with increasing efficiency and longer operating lifetimes. With the observation that a 1350 MWe nuclear reactor operating at a plant availability factor greater than 80% generates about 10 TWh per year, the approximate number of nuclear power plants (No.NPP) that could be needed ranges from 0 to about 3500 NPPs. The latter number (for total replacement of fossil fuel vehicles) with 50% renewable energy compares to the number 2920 (Kruger, 2001) for meeting the shortfall in electric energy in 2050 of 29.2 PWh with 40% renewable energy (including hydroelectric energy).

Conclusions

The model results, updated from those prepared five years ago (Kruger, 2001), show a more acute need to plan for a larger than business-as-usual growth in electricity demand over the next 50 years, especially if the hydrogen fuel age becomes significant after 2030 following a large growth rate in worldwide hydrogen fuel cell vehicle production after initiation in 2010. Although it would be difficult to abandon production of fossil fuel vehicles over this time period, some substitution of fossil fuels by hydrogen fuel, either by reforming or electrolysis, will be required. If the 30-40% per year growth rate of hydrogen fuel cell vehicle production can be achieved through the 40 years from 2010, the need for additional low-cost electric energy will become greatly increased. Three ways to assist in this transition may become available.

The first is a change in the economics and design of new installed electric power plants. As suggested by Boardman, Hunsbedt, and Kruger (1994) to the U.S. Department of Energy, the incremental cost of producing hydrogen by electrolysis of water at large power plants could be reduced significantly if the plants were designed for capacity well above the peak power demand instead of the normal few percent. This concept of a "dual-purpose power plant" is illustrated in *Figure 5*. With much of the operating and maintenance costs covered in the electricity cost, commercial quantities of excess electric power would always be available to produce hydrogen fuel at the marginal cost. The high-temperature cooling water from such large plants could be used to preheat the electrolysis feed water, which would synergistically reduce the electricity energy consumption per kilogram of hydrogen produced.

A second way to improve availability of hydrogen fuel would be the realization of the potential to produce hydrogen by high-temperature thermochemical decomposition of water. The commercial success of large-scale thermal decomposition of water into molecular hydrogen and oxygen depends on reducing the necessary temperature of >1500^{o}C for direct thermolysis of water to temperatures below 1000^{o}C which are available in modern (and future) electric power plants. This concept has been suggested for commercial operation at high-temperature nuclear power plants in several production cycles. A review of some 25 suggested thermochemical cycles was made by Brown et al (2000), from which two cycles were selected as the most promising. The first was the 3-step Sulphur-Iodine (S-I) cycle described by Besenbruch (1982) and the second was the 4-step Adiabatic UT-3 cycle described by Yoshida, et al. (1990). Study is currently underway to match the characteristics of the cycles to optimum nuclear reactor types. The type selected for the S-I cycle was the Modular Helium

Reactor described by Schultz (2003) and the Advanced High-Temperature Reactor described by Forsberg (2003). A schematic of the S-I process which requires a maximum temperature of about 830°C is shown in *Figure 6*. A somewhat smaller maximum temperature of about 750°C is required for the UT-3 cycle with 2 of the 4 reactions operating at about 600°C.

The third way to improve the availability of adequate electric power capacity would be the construction of Solar-Nuclear-Hydrogen Energy Parks (Kruger, 2002) distributed among the many industrially developed and developing nations of the world. These facilities would be located in large area industrial parks in remote high solar insolence areas with a central cluster of nuclear power plants surrounded by a field of photovoltaic cells, possibly with a bank of wind power mills on the high side, and the generator and electrolysis (or thermochemical) equipment near the delivery side. This synergistic coupling would reduce problems associated with choice of energy resource: namely, the unpopularity of high specific energy of nuclear energy (10^{11} kJ/kg) and the technical problems of low specific energy (10^4 kJ/kg) from solar power. These parks could be provided with "dual-purpose power plants with reduction" of the cost of hydrogen fuel by solar preheating for higher-temperature electrolysis.

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Figures:

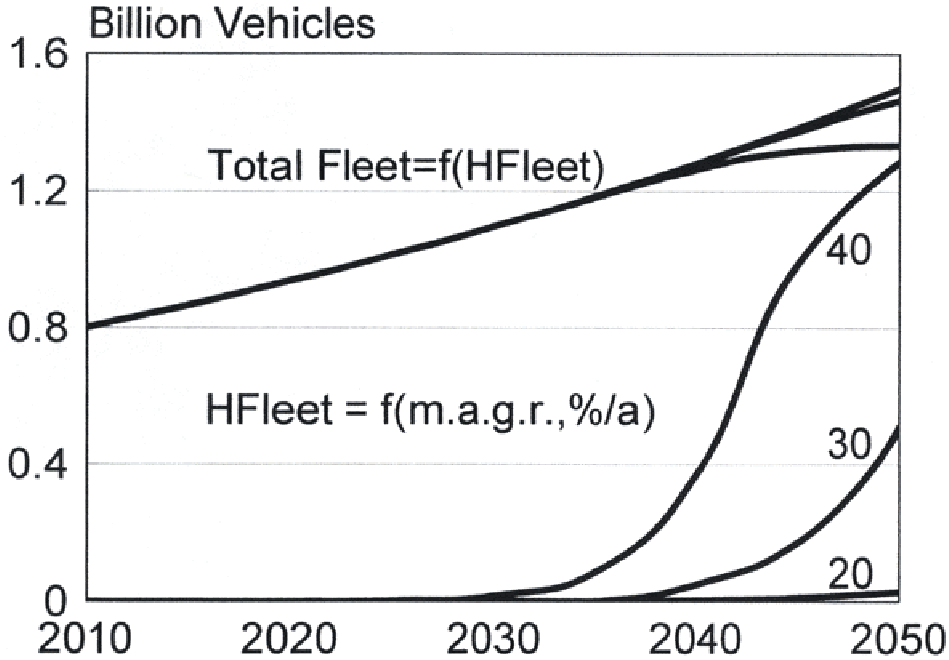

Fig. 1. World HFleet as function of total fleet.

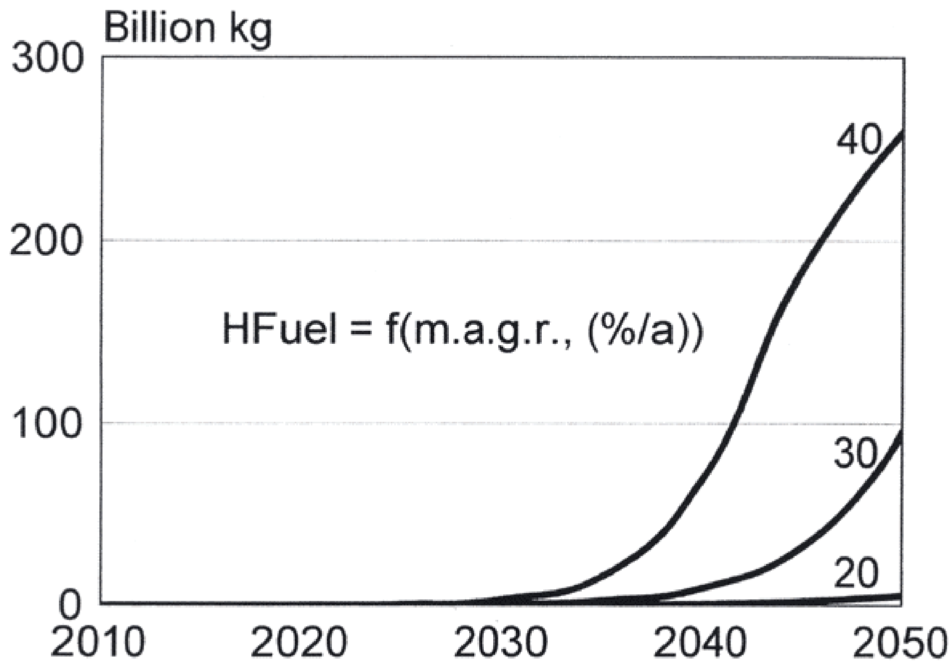

Fig. 2. World HFuel Requirement for HFleet.

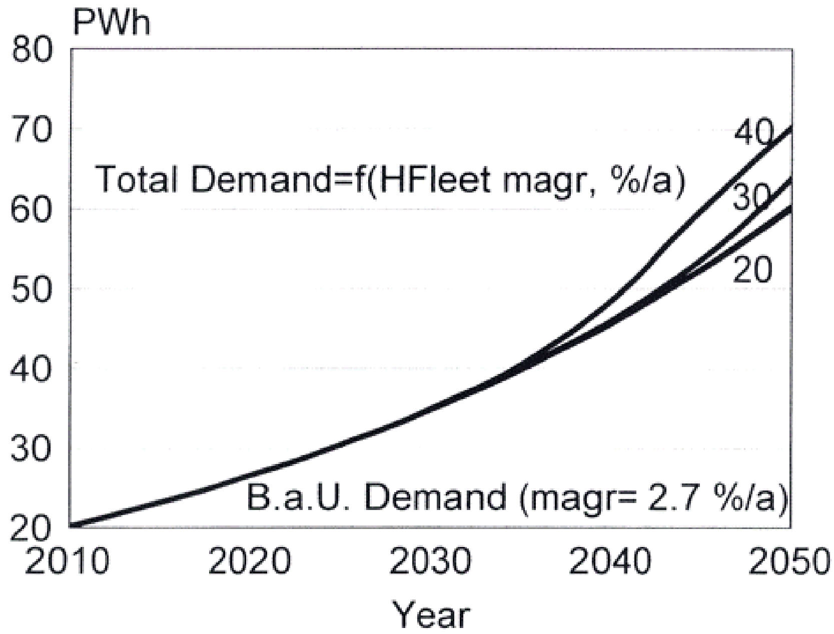

Fig. 3. Total electric energy demand.

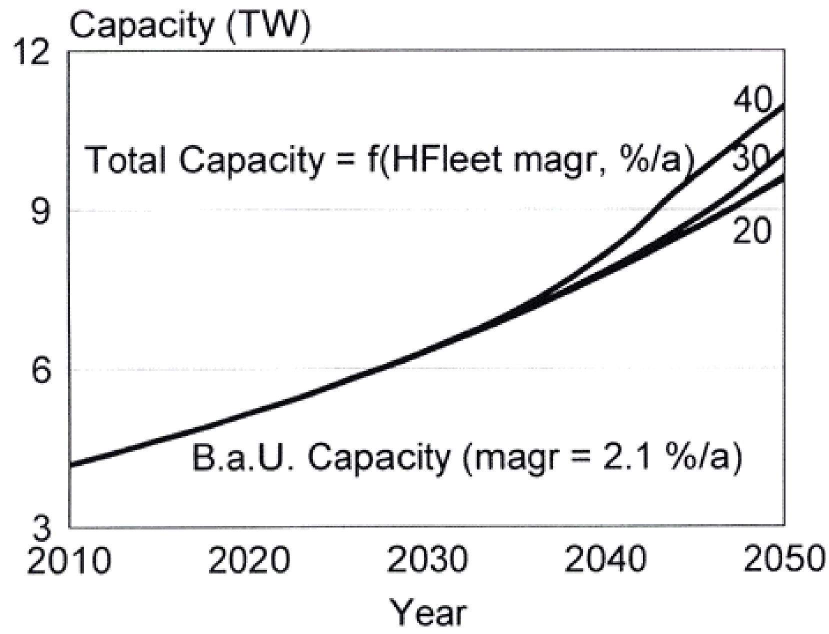

Fig. 4. Total electric power capacity.

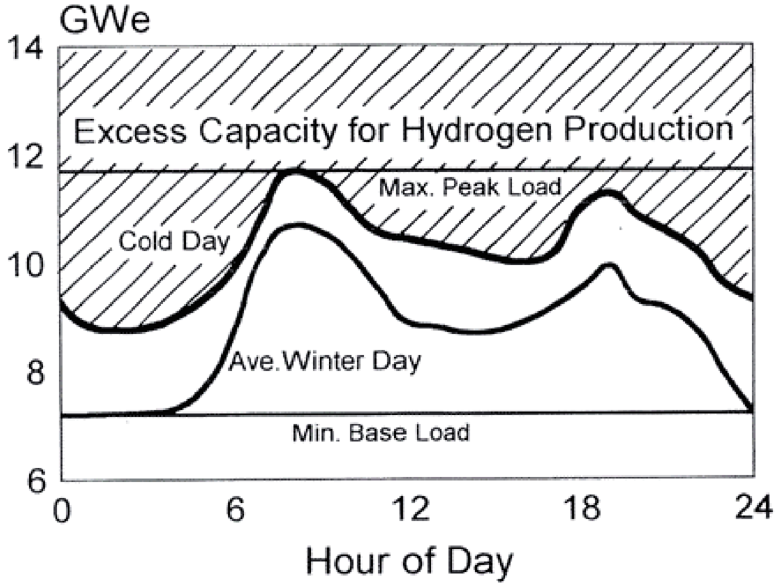

Fig. 5. Dual-purpose power plant concept.

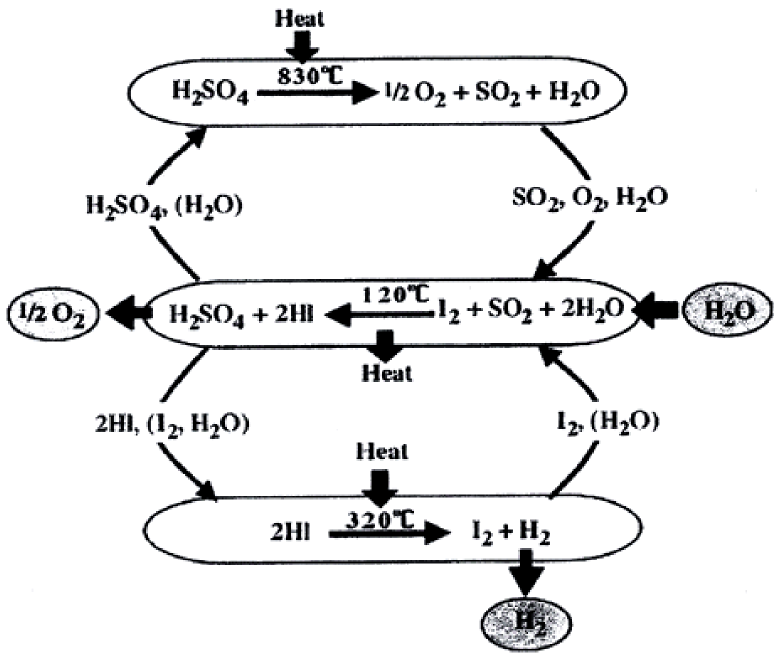

Fig.6. Schematic of S-I cycle (Schultz, 2003).