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Inertial Fusion Energy Power Plants Based on Laser or Ion Beams*

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ABSTRACT

Two example inertial fusion energy power plants are discussed; one driven by ions based on more well known principles and the other by short pulsed lasers in a mode called fast ignition based on more speculative and unproven processes. The calculated cost of electricity for 2 GWe size plants is 4.0 and 3.3 ¢/kWh for the ion and laser driven power plants which can be compared to predicted cost of electricity made by coal, fission, and natural gas at today's prices of 6.6, 4.9, and 3.0 ¢/kWh. These rather remarkable results are based on yet to be proven targets, low cost drivers and use of a neutronically thick layer of liquid Flibe facing the microexplosion. Final laser optics made of a liquid metal film are predicted to last the life of the plant. The use of liquids appears to solve the first wall materials problem that has dogged fusion plant concepts and allows reduced chamber costs, allows higher plant capacity factors and fewer plant components that would otherwise be needed to replace damaged chamber walls. Also the development program to achieve a practical fusion power plant could be down sized.

Introduction

HYLIFE-II [1,2] (see Fig. 1) is a power plant design based on surrounding targets with a thick layer of liquid Flibe, (Li_2BeF_4) so that the chamber and other apparatus can stand up to bursts of energy at ~7 Hz without replacing components during the plant's 30-year life. With liquid protection the capacity factor will be increased and the cost of component replacement will be decreased. The design is robust to technology risks in the sense that if the performance of targets, drivers and other components fall short of predictions, the cost of electricity rises surprisingly little. Many of the performance parameters were varied (Ref.3) to show how robust the design was. In the present paper we redo the calculations based on recent ion driven target designs[4] and include examples of laser driven power plants shown in Fig. 2. The speculative fast ignitor target[5] can possible be driven from two sides[6] using plasma mirrors[7] to focus the short pulse laser light permitting the same liquid wall protected chamber as the ion driven case. The fast ignitor concept should work equally well with ion drivers if they can be focused and delivered in short enough time which is more a statement about the accelerator technology rather than target design.

The design strategy we recommend is (in so far as possible) to use conventional engineering principles and known materials in an optimized way to obtain the lowest cost of electricity while meeting rigorous safety standards and keeping the design robust to short falls in predicted cost and performance of components. For a number of components with a high technology risk we have fall-back options.[3] Low cost target production, practical heat and tritium recovery systems, and integrated beam focusing and reaction chambers will all have to be developed and demonstrated in a cost effective manor.

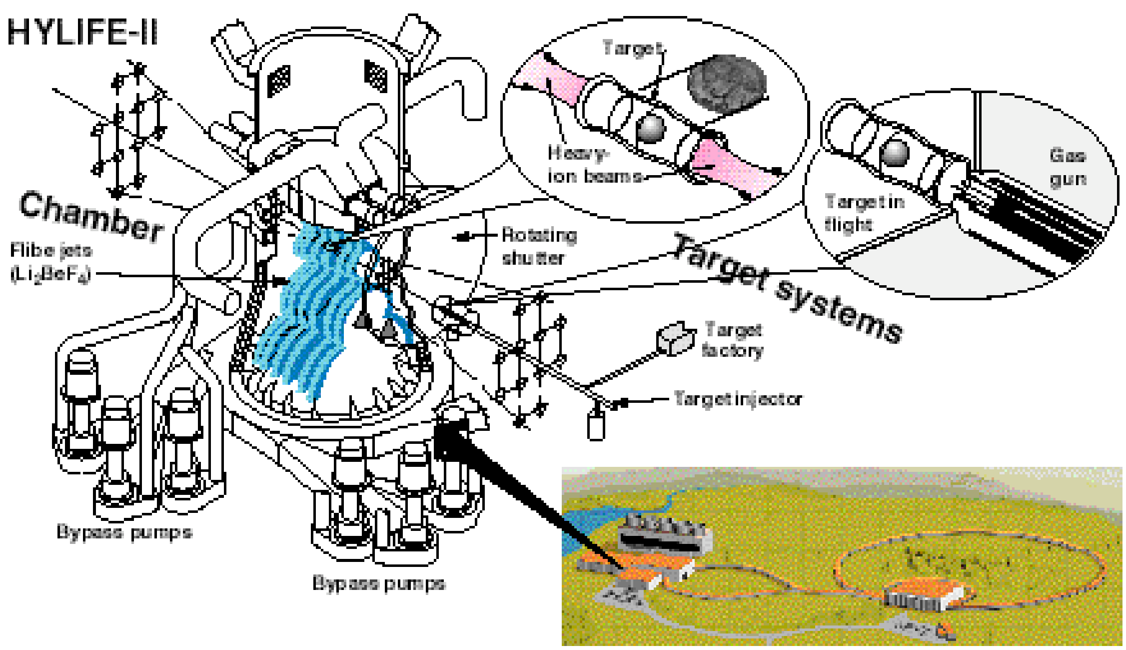

Figure 1. The HYLIFE-II-Ion beam driven, power plant is shown with a two-ended target, illuminated from two sides and a recirculating heavy-ion driver. The liquid wall protection including beam ports is provided by pumping molten salt (Flibe) through the chamber.

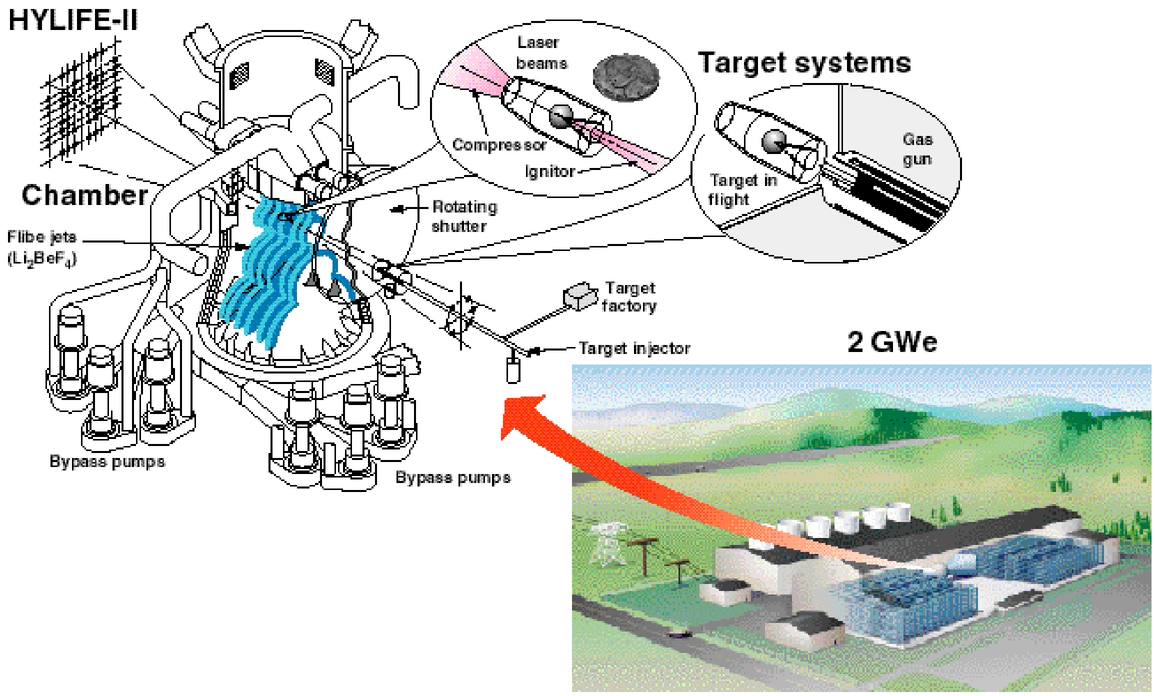

Figure 2. The HYLIFE-II-Laser driven, power plant is shown with a two-ended fast ignitor target. Slow laser compression beams enter from the left and fewer short pulse lasers enter from the right as shown.

Plant Design

The four main systems of the plant are shown in Fig. 1 and 2 (target, chamber, driver and power plant). The ion driven target of Fig. 1 is based on "hot spot ignition" discussed in Ref. 4 and has been verified with 2-D radiation/hydro computer simulations (LASNEX). Experimental confirmation of hot spot ignition awaits the National Ignition Facility. The laser driven target of Fig. 2 is based on cold compression followed by heating a small spot to ignition with an extremely short duration pulse of energy—a process called fast ignition—and has not yet had radiation/hydro computer simulations carried out. Woodworth and Meier discuss the state of knowledge on target production.[8] Petzoldt discusses the system that accurately injects these targets into the reaction chamber about 5 times a second.[9] Nominal plant parameters are given in Table 1.

Table 1
Nominal Plant Parameters

	Ion-beam 1 GWe	Ion-beam 2 GWe	Laser 1 GWe	Laser 2 GWe
Driver energy, MJ	5.5	7	1.0	1.5
Target gain	60	78	371	486
Yield, MJ	327	547	371	729
ηG	20	27	32	42
Repetition rate, Hz	7.0	8.1	6.0	5.9
Fusion power, MW	2284	4418	2210	4318
Thermal power, MW	2724	5239	2605	5075
Gross electrical power, MWe	1171	2253	1120	2182
Recirculating power, MWe	171	253	120	182
Bypass pumping power (Flibe), MWe	36	51	32	42
Driver input power, MWe	115	164	69	103
Other pumping power*, MWe	20	38	19	37
Net electricity power, MWe	1000	2000	1000	2000
Calculated cost of electricity, ¢/kWh	5.6	4.0	4.2	3.3

*Includes pumping power in the heat transport system and in the steam generator. The capacity factor is 85%, thermal efficiency is 43%, blanket energy multiplication is 1.18.

Cost Analysis

We have made cost estimates (see, for example, Ref. 1,2,10,11) of the plant components and compute cost of electricity using Delene's recommended non-inflating levelization method.[12]

We show two reference cases at 1 GWe or 2 GWe size for both ion and laser drivers with the parameters in Table 1.

New target performance

The recently calculated target performance (Ref. 4) is shown as a point in Fig. 3, at 6 MJ of driver energy the yield is 400 MJ for a gain of 67. A gain curve from Ref. 13 going through this point was used to scale to different energies. Families of curves are plotted to show enhanced performance in this, and in Ref. 3 degraded performance gain curves were studied. The laser gain curve (Fig. 4) for direct drive and fast ignitor are based on work by Lindl.[14]

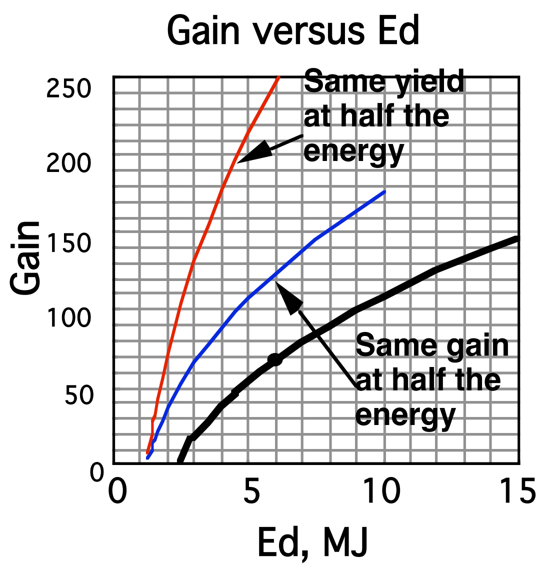

Fig. 3. Target gain versus ion driver energy.

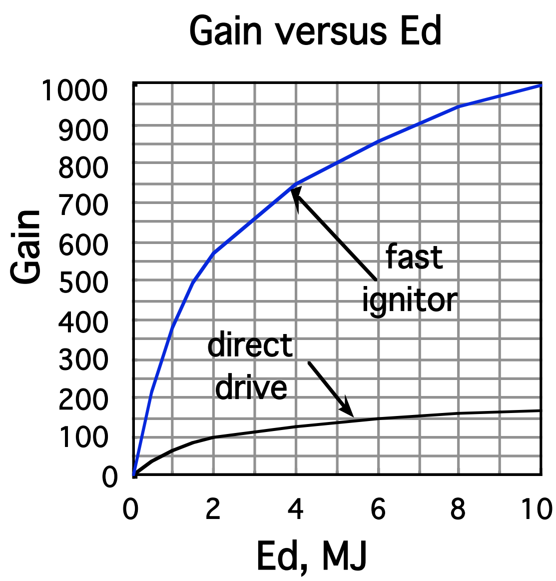

Fig. 4. Target gain versus laser driver energy.

New Driver cost model

The ion driver cost used in this paper is based on preliminary work by Wayne Meier (Ref. 15) and labeled in Fig. 5 as, “Meier’s model,” along with a number of past estimates[16,17,18] for comparison. His result is approximately Cd = 297 + 109•Ed direct cost in millions of current dollars with driver energy, Ed, in MJ. A survey of the literature on driver cost analyses is shown in Fig. 5 for comparison. The driver cost labeled HIBALL-II [17] is based on RF accelerator and storage ring technology (of about 1984). The cost estimate was 1800 M$ (1995). The design labeled HIFSA [18], 1100 M$ at 4.5 MJ was based on induction accelerator technology of mid 1980’s. The laser driver direct cost assumed in 1995$ was 1122 $(Ed/3.68\ MJ)^{0.7}$, M$, based on a diode pumped solid state laser studied[19] at 3.68

MJ at 0.35 μm. Since the driver energy for the design point chosen in Table 1 (1 and 1.5 MJ for 1 and 2 GWe) is so far from that of Ref. 19 in both energy and pulse length, the scaling can be considered dubious and needs further work.

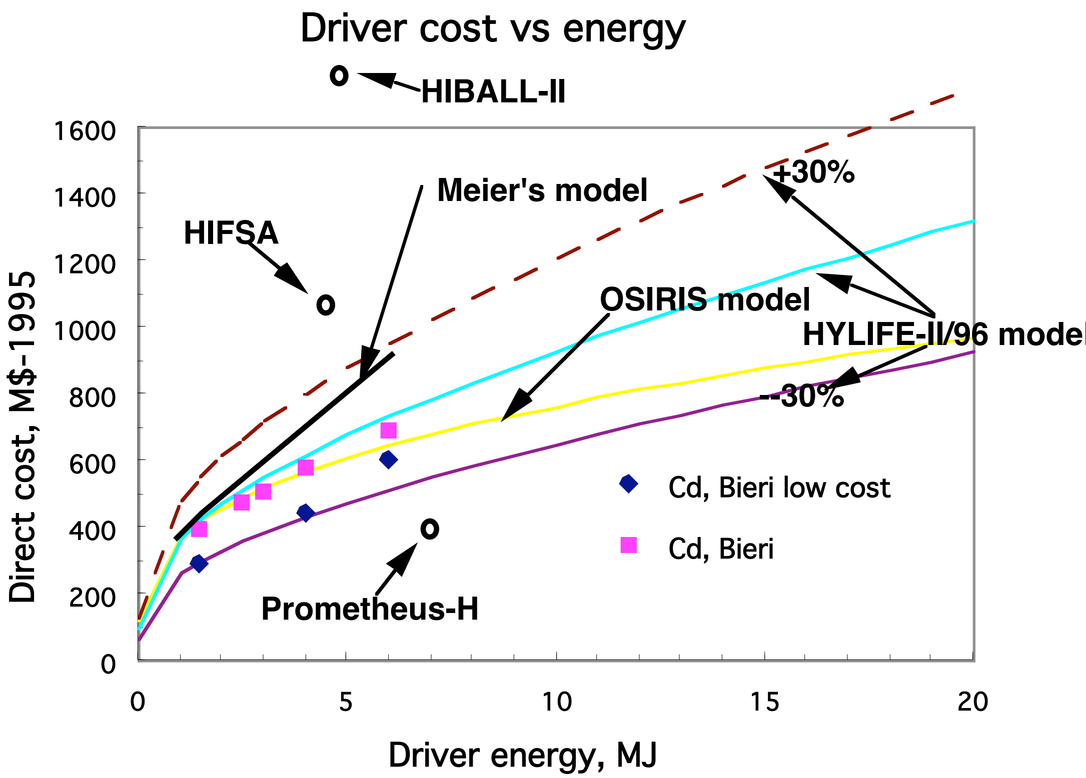

Figure 5. Driver cost versus driver energy is parameterized for this study with comparisons to the results from published design studies.

COE versus driver energy

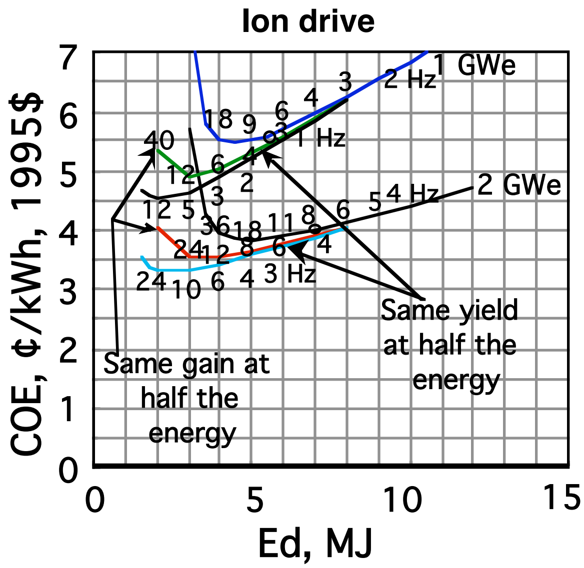

Figure 6. COE versus ion driver energy.

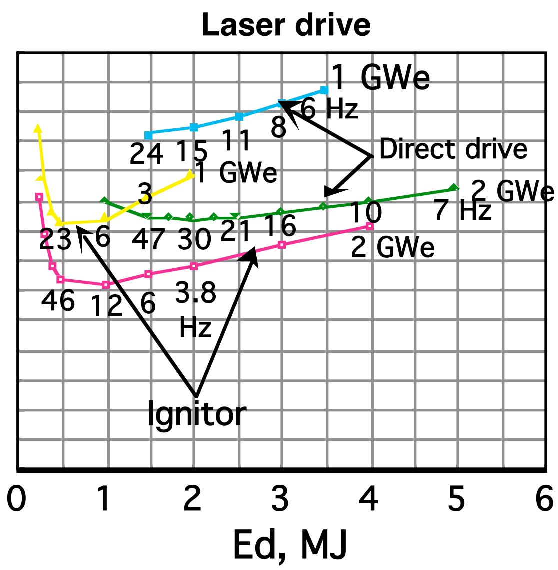

Figure 7. COE versus laser driver energy.

Cost of electricity-ion driver

With the new gain curves and new driver cost algorithm, the cost of electricity was computed for a number of cases using the usual assumptions discussed in previous HYLIFE-II papers.[1,2,3] In Fig. 6 the cost of electricity is plotted with the pulse rate given at many points along the curves for the gain curves shown in Fig. 3. The COE rises from the minimum point as the driver energy increases due to increasing driver cost. The COE also rises from the minimum point as the driver energy decreases due to, 1- the increased recirculating power to the driver (lower gain), 2- the increased cost of pumps and pumping power to circulate the liquid to protect the walls at increasing rates and, 3- somewhat due to increased cost of targets. The preferred operating point rather than be at the minimum might be at 5.5 MJ and 7 MJ for 1 and 2 GWe total power to keep the pulse rate so that chamber clearing doesn't become a more critical feasibility issue than it already is. For example, from Fig. 6 if 18 Hz were allowed rather than 8 Hz, the COE would drop from 4.0 to 3.8 ¢/kWh for a 4% reduction for ion drivers at 2 GWe. This finding lends importance to chamber phenomena research that will emphasize chamber clearing at high pulse rates. For the enhanced gain curves the COE is lower and the preferred operating point moves to lower driver energy.

Cost of electricity-laser driver

The cost of electricity was calculated using the laser gain curves shown in Fig. 4 for direct drive and the fast ignitor. The fast ignitor curve is simply six times the direct drive case (Ref. 6 and 14). As before we chose an operating point not at the cost minimum but somewhat higher where the pulse rate is thought to raise fewer chamber clearing feasibility issues. If 12 Hz were allowed rather than 6 Hz, the COE would drop from 3.2 to 3.1 ¢/kWh for a 4% reduction for laser drivers at 2 GWe. At 1.5 MJ driver energy the pulse rate is 5.9 Hz and the COE is 3.3 ¢/kWh. The ignitor curves are always lower than the direct drive case because of the cost advantages of liquid walls and lower recirculating power.

Effect of ion driver cost

The single largest cost item in the plant is the driver. The cost of electricity for a driver energy of 7 MJ whose cost is 1060 M$ direct cost, is 4 ¢/kWh of which the driver represents 39% of the total. A 10% change in driver cost results in a 4 % change in COE. If the driver cost should go up by 30% to 1400 M$ the COE increases to 4.5 ¢/kWh. If the cost of the driver is zero the COE is 2.5 ¢/kWh.

Effect of power

As the power increases the cost of the driver becomes a smaller proportion of the total cost. There are other smaller but significant economies of scale for the other plant components as well. The COE as a function of net electric power for the laser-driven, fast ignitor-target case is shown in Fig. 8 at variable power. By following this curve out we can see the COE drop to values where making hydrogen by electrolysis to power vehicles can approach that of today's cost of gasoline. Electricity at 2.5 ¢/kWh can be used to make hydrogen at $12/GJ which can power hybrid cars equivalently to gasoline at $1.40/gallon.[11] In large plant sizes of >5 GWe the cost of electricity might be this low as shown in Fig. 8.

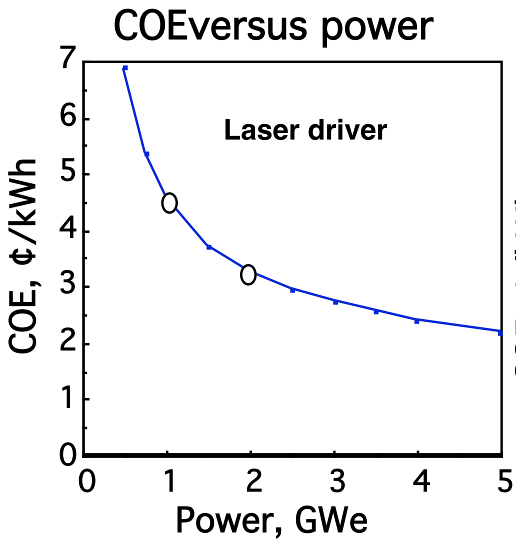

Figure 8. Cost of electricity (COE) versus power for laser driven targets.

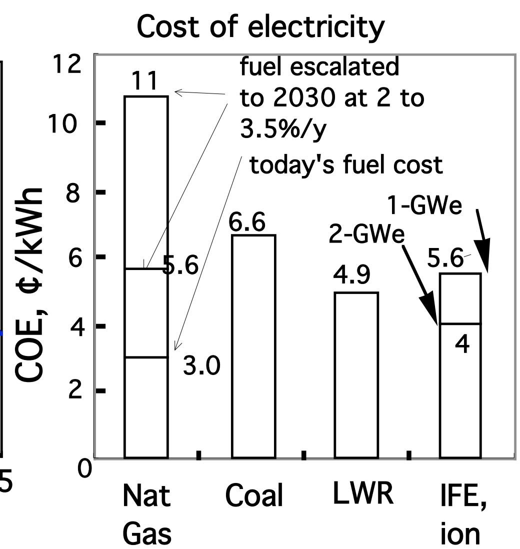

Figure 9. Cost comparisons of heavy-ion IFE with other options.

Cost comparisons to coal, natural gas and fission

To put the above cost of 5.5 and 4.0 ¢/kWh for 1 and 2 GWe size ion driven plants in perspective, we compare to other options based on work by Delene.[12] For coal in optimum sizes (~600 Mwe), he quotes at 6.6 ¢/kWh. Nuclear fission is 4.9 and 4 ¢/kWh in 1 and 2 GWe sizes. Safety designs of fission plants emphasizing inherent processes such as natural circulation for safety tend to favor smaller size plants. For natural gas he quotes 3 ¢/kWh with today's low cost fuel. The MFE tokamak costs are about 6.5 ¢/kWh and up at 1 GWe size. With their non-liquid walls, they have difficulty in scaling to higher powers due to wall load limits. Even with the expensive driver, it appears the cost of electricity calculated for ion and laser driven IFE is lower than coal and tokamaks, and is on a cost par or lower than fission power, especially when IFE is scaled to large power units (~2 GWe). Of course, natural gas wins by a wide margin with its low cost and ease of use. While natural gas is currently the lowest cost option, its cost can be expected to increase due to depletion, to cost of carbon sequestering or to carbon emission taxes. These comparisons are shown in Fig. 9.

A question naturally comes up, does anyone believe our cost calculation for IFE of 4.0 and 3.3 ¢/kWh power at 2 GWe for ion and laser driven IFE? The present discussion is useful more to see trends, what is important, and where the high leverage items are than in predicting the eventual cost of electricity. Clearly, target performance, plant power, and low cost drivers are the high leverage items. Also the combined savings from the use of liquid walls are essential for low cost of electricity. However, the results are so important that independent studies should be made to verify these calculations. Many of the predictions are based on assumptions that will only be proven by carrying out R&D. If the results are believed to be valid then actions should be taken to fund the R&D needed to bring this energy option to reality.

Conclusion

An ongoing study of the HYLIFE-II design with both ion and laser drivers has resulted in considerable improvement and more realistic assumptions. Continuation of this effort can be expected to make more improvements and add more realism to the basic design. The cost of electricity minimizes at a high pulse rate to lower the driver energy and therefore its cost. This finding emphasizes chamber phenomena research directed at chamber clearing to permit high pulse rates of twice the usual values of 6 to 8 Hz. If the target performs well and if the driver cost is < 1 B$ direct, the cost of electricity is predicted to be less than that from fossil and fission energy, and hydrogen production used for transportation fuels might be realistic in large sizes.

Acknowledgments

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Expansion of data from Table 1, page 4

Plant Cost Breakdown for Ion and Laser Driven IFE 1000 MWe

		Ion Driver-1 GWe (millions 1995$)		Laser Driver-1 GWe (millions 1995$)	
Acct	Item	R+D+TF[1]	BOP	R+D+TF[1]	BOP
20	Land and land rights		12.7		12.7
21	Structures/improvements	66.2	855.7	64.5	83.8
22	Reactor plant equipment				
22.1	• Reactor, BP pumps, pipe				
	• Reactor	34.4		35.3	
	• Bypass pumps	67.6		65.6	
	• Bypass pipe	11.3		16.6	
22.2	Flibe coolant	34.5		33.2	
22.3	Vacuum system (in 22.5)				
22.4	Target factory and equipment	64.9		59.5	
	Target injector				
22.5	Tritium management system	61.8		59.9	
22.6	Shielding (in Acct. 21)				
22.7	Heat transport system				
	• Coolant piping		7.9		7.5
	• Coolant valves and bellows		18.2		17.4
	• Pump and motors		43.5		41.6
	• Coolant cleanup		18.9		18.1
	• Steam separators		11.5		11.0
	• Water loop piping		0.2		0.2
	• Steam generators		81.5		78.0
22.8	Remote maintenance equip't	50		50	
23	Turbine plant equipment		218.9		210.3
24	Electric plant equipment		69.0		66.3
25	Misc. plant equipment		26.5		25.5
26	Main heat rejection system		36.4		35.2
27	Driver equipment	896.5		450.7	
	Total direct cost	1287.3	630.9	835.4	607.5
		1918.2		1442.9	
	Indirect cost factor	1.936	1.936	1.936	1.936
	Subtotal	2492.2	1221.4	1617.3	1176.1
	Total Capital Cost	3713.6		2793.4	
	Capital cost/kWe	3714		2793	
	COE for capital[2] (¢/kW/hr)	3.23	1.58	2.10	1.53
	COE for O&M/SCR[3]/Fuel	0.52	0.25	0.34	0.24
	Total COE	5.59		4.21	

[1]Reactor + Driver + Target Factory.
[2]The assumed availability was 85%, the capital rate for non-inflating dollars was 9.66%.
[3]Scheduled component replacement and operations and maintenance annually costed at 3% of direct cost.

Expansion of data from Table 1, page 4

Plant Cost Breakdown for Ion and Laser Driven IFE 2000 MWe

		Ion Driver-2 GWe (millions 1995$)		Laser Driver-2 GWe (millions 1995$)	
Acct	Item	R+D+TF[1]	BOP	R+D+TF[1]	BOP
20	Land and land rights		12.7		12.7
21	Structures/improvements	101.4	118.8	99.1	116.9
22	Reactor plant equipment				
22.1	• Reactor, BP pumps, pipe				
	• Reactor	54.6		58.7	
	• Bypass pumps	105.5		103.3	
	• Bypass pipe	17.8		16.6	
22.2	Flibe coolant	61.2		59.5	
22.3	Vacuum system (in 22.5)				
22.4	Target factory and equipment	74.4		63.6	
	Target injector				
22.5	Tritium management system	101.8		99.2	
22.6	Shielding (in Acct. 21)				
22.7	Heat transport system				
	• Coolant piping		15.1		14.6
	• Coolant valves and bellows		35.0		33.9
	• Pump and motors		83.7		81.0
	• Coolant cleanup		36.4		35.3
	• Steam separators		22.0		21.3
	• Water loop piping		0.3		0.3
	• Steam generators		156.8		151.9
22.8	Remote maintenance equip't	75.8		75.8	
23	Turbine plant equipment		379.4		370.2
24	Electric plant equipment		119.6		116.7
25	Misc. plant equipment		46.0		44.8
26	Main heat rejection system		63.4		62.1
27	Driver equipment	1060		599	
	Total direct cost	1652.5	1089.3	1174.4	1061.8
		2741.8		2236.2	
	Indirect cost factor	1.936	1.936	1.936	1.936
	Subtotal	3199.2	2108.8	2273.6	2055.6
	Total Capital Cost	5308		4329.2	
	Capital cost/kWe	2654		2165	
	COE for capital[2] (¢/kW/hr)	2.08	1.37	1.47	1.33
	COE for O&M/SCR[3]/Fuel	0.33	0.22	0.24	0.21
	Total COE	4.00		3.26	

[1] Reactor + Driver + Target Factory.

[2] The assumed availability was 85%, the capital rate for non-inflating dollars was 9.66%.

[3] Scheduled component replacement and operations and maintenance annually costed at 3% of direct cost