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Abstract. A variety of systems analyses have been conducted for laser driver IFE power plants being developed as part of the High Average Power Laser (HAPL) program. A key factor determining the economics attractiveness of the power plant is the net power conversion efficiency which increases with increasing laser efficiency, target gain and fusion-to-electric power conversion efficiency. A possible approach to increasing the power conversion efficiency is direct conversion of ionized target emissions to electricity. One chamber design being considered for HAPL is called the magnetic intervention approach where a cusp magnetic field is used to deflect ions into external dumps, thus protecting the chamber first wall. A possible option with such a design would be to inductively couple the expanding plasma to an external circuit allowing some of the ion energy to be directly converted to electricity. This study examines the potential benefits of increased efficiency achieved with such an approach. Results are evaluated parametrically considering the fraction of fusion energy in ions and the ion-to-electricity conversion efficiency. For base case direct-drive targets with approximately 24% of the target yield in ions, the benefits are modest, especially for chamber designs that operate at high temperature and thus already have relatively high thermal conversion efficiencies. The reduction in the projected cost of electricity is ~5-10% assuming the cost of direct conversion is no higher than thermal conversion. Details of the systems model and parametric studies are presented.

1. Introduction

The High Average Power Laser Program (HAPL) is conducting research on laser-driven IFE power plants based on direct-drive targets and dry-way chambers. Systems modeling in support of this program have been used to identify the design features with high leverage for improving power plant economics and evaluating design trade-offs [1]. A key factor determine the economic attractiveness of the power plant is the net power conversion efficiency, η_{net}, which increases with increasing laser efficiency, target gain and fusion-to-eclectic power conversion efficiency as indicated in equation (1).

$$\eta_{net} = \eta_c \cdot \left[1 - \frac{1}{\eta_L \cdot G \cdot M \cdot \eta_c} \right] \qquad (1)$$

where

η_L = laser wall-plug efficiency,

G = target gain,

M = overall energy multiplication factor,

η_c = power conversion efficiency.

For a typical design where the chamber coolant flows to heat exchangers and drives a steam or Brayton cycle, η_c is just the thermal-to-electric conversion efficiency. A possible approach to increasing η_c is direct converse of the ionized target emissions to electricity. One chamber design being conceded for HAPL is called the magnetic intervention approach [2,3] where a cusp magnetic field is used to deflect ions into external energy dumps thus protecting the chamber first wall from ion bombardment. A possible option with such a design would be to inductively couple the expanding plasma to an external circuit allowing some of the ion energy to be directly converted to electricity [4]. This study examines the potential benefits of increased conversion efficiency using this approach.

Section 1 briefly describes the systems model and base case assumptions; Section 2 presents results on the sensitivity of the cost of electricity (COE) to laser efficiency, target gain and power conversion efficiency in a generic sense; Section 3 examines the specific case of using direct conversion to increase conversion efficiency; and Section 4 contains the conclusions and recommendations.

2. Model and assumptions

The laser IFE power plant system model includes cost and performance models for the target, laser, fusion chamber, and balance of plant (BOP). It is based on the W-armor coated ferritic steel dry-wall design with liquid lithium coolant [1]. We use this model to determine the potential benefits of direct conversion assuming costs for such a design would be comparable. If a detailed design of a direct conversion chamber is developed, the systems model can be modified to more accurately reflect chamber cost and scaling. The major costs of the power plant, i.e., the laser, target factory, and BOP equipment and facilities, will be similar, so the results presented here are judged to be quite representative of what we expect to find with detailed magnetic intervention chamber model. As a first step, we assume that the cost of direct conversion equipment is the same as thermal conversion on a $/kW$_t$ basis.

For this study, we have selected a particular example reference case for comparison; the key parameters are given in Table 1.

Table 1. Parameters for example reference case.

Driver energy (E_L)	2.31 MJ
Target gain (G)	105
Yield (Y)	242 MJ
Rep-rate (RR)	10 Hz
Fusion power (P_f)	2421 MW
Energy multiplication (M)	1.13
Thermal power (P_t)	2736 MWt
Conversion efficiency (η_c)	45%
Gross electric power (P_g)	1231 MWe
Laser efficiency (η_L)	10%
Laser power (P_L)	231 MWe
Net electric power (P_n)	1000 MWe
Net plant efficiency (η_{net})	36.5%

The reference case is a diode-pumped solid state laser (DPSSL) with a 10% wall-plug efficiency and total beam energy of 2.31 MJ. The corresponding direct-drive target gain for 0.35 μm light (3ω) is 105 giving a target yield of 142 MJ [5]. The example case power conversion efficiency is 45%, which is consistent with a chamber design using ODS ferritic steel (peak temperature of 750-800 °C) and Brayton power cycle. The pulse repetition rate (rep-rate) is set at 10 Hz. This is somewhat less than optimum for this power plant, but is judged to be a reasonable, although challenging, operating point. The net electric power (= gross electric power - laser power) is 1000 MWe. Other key parameters are also listed.

We use the cost of electricity as the figure of merit for evaluating design trade and sensitivity studies. The COE in ¢/kWeh is given by

$$COE = \frac{FCR \cdot TCC + OM}{0.0876 \cdot P_n \cdot CF} + D \tag{2}$$

where
FCR = fixed charge rate (0.0966/yr),
TCC = total capital cost of the power plant, \$M,
OM = annual operation and maintenance cost, \$M,
P_n = net electric power, MWe,
CF = annual capacity factor (= 0.85),
D = decommissioning allowance (= 0.05 ¢/kWeh), and
0.0876 = conversion factor = (8760 h/yr) × (1000 kW/MW) × (10-8 \$M/¢).

The COE is simply the annual expenses to cover the plant capital investment, operating and maintenance divided by the annual net energy produced. We have assumed an annual capacity factor of 85% in this study. The COE for the reference case point is 6.6 ¢/kWeh.

3. Results

3.1. Sensitivity to laser efficiency, power conversion efficiency and target gain

Before we consider the case of direct conversion, we examine the sensitivity of the COE to the various factors that affect the net plant conversion efficiency, i.e., laser efficiency, power conversion efficiency and target gain.

Figure 1 shows the COE as a function of the laser efficiency in the range from 5-15%. Note in this analysis the net electric power, P_n, and rep-rate are held constant. Therefore, as η_L varies, the laser energy (and thus target gain) changes to keep P_n fixed. Under these assumptions, the COE increases by 13% as η_L decreases from 10% to 5%, and the COE decreases by 4% as η_L increases to 15%.

If we hold driver energy, gain, yield and rep-rate constant as η_L varies, the net power changes and the COE varies more. At 5%, the net power decreases to 769 MW_e , and COE is ~8.6 ¢/kWeh (+30%). At 15%, P_n = 1077 MWe, and COE = 6.1 ¢/kWeh (-7%). The author's opinion, however, is that it is best to compare results for a fixed net electric power since that is the produce of the plant.

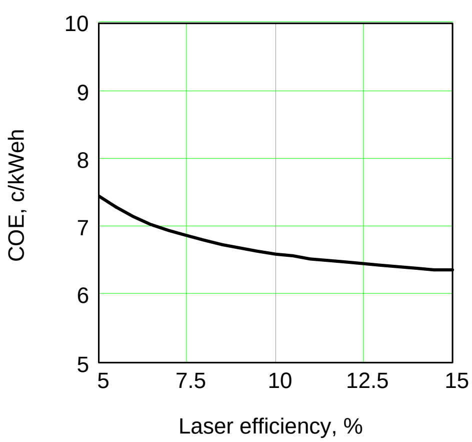

Figure 1. COE versus laser efficiency. Net power is fixed at 1000 MWe

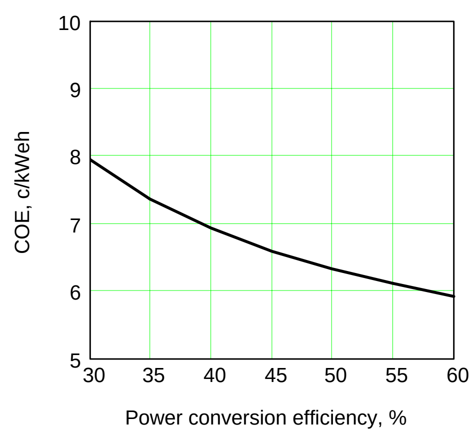

Figure 2. COE versus power conversion efficiency. Net power is fixed at 1000 MWe

Figure 2 give the COE as a function of the power conversion efficiency over a broad range about the reference case of 45%. Again, P_n and rep-rate are held constant while the laser energy and target gain vary as η_L varies. As seen, power conversion efficiency has a significant impact on COE, particularly if it is reduce from 45%. At η_c = 30%, the COE is 20% higher, while at η_c = 60%, the COE is down by 11%. Achieving power conversion efficiencies > 50% with thermal cycles will require development of advance high temperature chamber materials such as SiC that are capable of operating at temperatures much higher than even ODS ferritic steel.

Examination of equation (1) shows that net efficiency scales linearly with η_c. Figure 3 shows the normalized net efficiency as a function of the relative changes in laser efficiency, target gain, and power conversion efficiency. Equivalent changers in target gain and laser efficiency have the same impact; both affect the recirculating power for the laser.

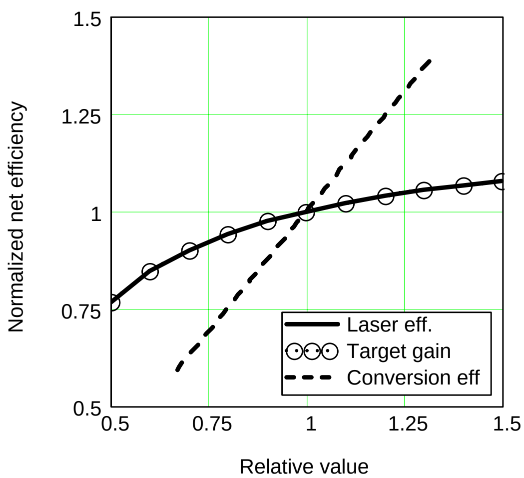

Figure 3. Normalized net efficiency as a function of relative changes in laser efficiency, target gain and power conversion efficiency. Laser efficiency and power conversion efficiency curves overlay each other.

3.2. Power plant using direct conversion

Direct conversion allows conversion efficiency to exceed the thermal cycle efficiency, thus given higher net plant efficiency. To account for this possibility and evaluate the effects on the COE, the following equation (3) for η_c is substituted in equation (1).

$$\eta_c = \frac{f_i \cdot \eta_i + \left[(1 - f_i) \cdot M_n + f_i \cdot (1 - \eta_i)\right] \cdot \eta_t}{M} \qquad (3)$$

where

f_i = fraction of target yield in ions,

η_i = ion-to-electric conversion efficiency,

M_n = neutron energy multiplication factor,

M = overall energy multiplication factor, and

η_t = thermal-to-electric conversion efficiency.

Equation (3) assumes that the ion energy that is not directly converted, $f_i \cdot (1-\eta_i)$, is available for thermal conversion as the same efficiency (η_t) as the other chamber energy from neutrons and x-rays. Figure 4 shows the power flow diagram for this concept. For the reference case direct-drive target and dry-wall chamber design, f_i = 0.24, M_n = 1.17, and M = 1.13.

Figure 5 show the power conversion and net pant efficiency as a function of ηi using the case η_t = 0.45. If the ions can be converted directly at 50%, η_c increases from 45% to 51%, and the net plant efficiency (η_n) increases from 36.5% to 42.4%.

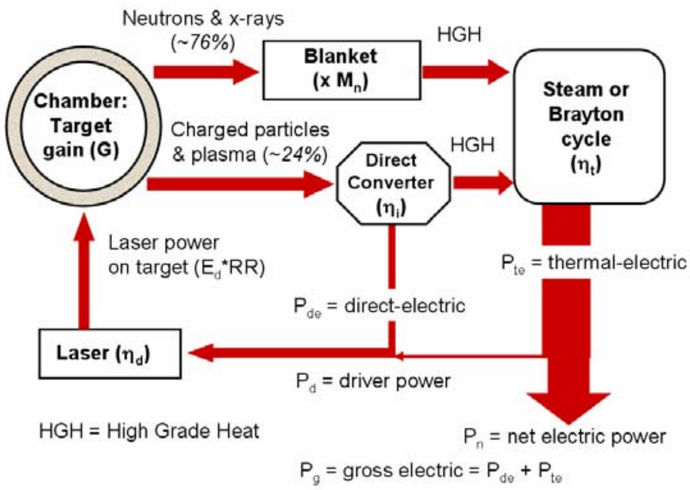

Figure 4. Power flow diagram for plant using direction conversion of ion energy.

Figure 6 shows the impact on the COE for different assumptions. The solid cure assumes P_n is fixed at 1000 MWe, and the rep-rate is held constant at 10 Hz, while E and G vary as η_i varies. In this case, the reduction in the COE (assuming no added cost for direct conversion equipment) is <5%. The dashed curve holds driver energy, gain and rep-rate constant (i.e, fixed fusion power), so P_n increases as η_i increases. In this case, the COE decrease by 11% for $\eta_i = 50\%$.

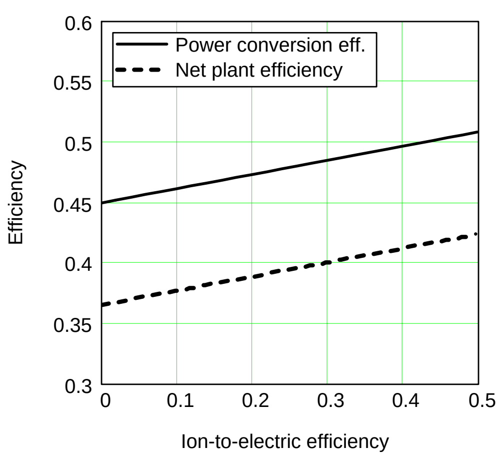

Figure 5. Power conversion efficiency (solid) and net plant efficiency (dashed) versus ion-to-electric conversion efficiency.

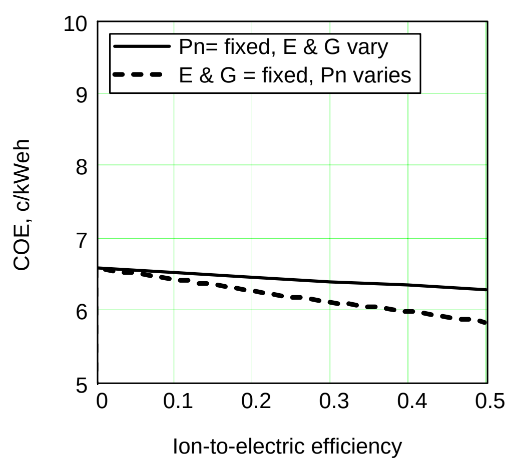

Figure 6. COE vs. ion-to-electric conversion efficiency for case of fixed net electric power (solid) and fixed fusion power (dashed). Rep-rate = 10 Hz in both cases.

Another way to evaluate the potential benefits of direct conversion is to determine the allowable additional capital cost to give the same COE. For the constant net power case, an addition $240M in total cost is allowed for $\eta_i = 50\%$. (Direct capital costs are about 2× lower.)

4. Conclusions

We have used the laser IFE systems code to evaluate the potential benefits of direct conversion of target ions to electricity. For the direct-drive target used in the HAPL study, the fraction of target yield in ions is only 24%, so the potential improvement in overall conversion efficiency is rather limited.

For the constant net power case, the COE is only reduced by ~5% if the ions are converted at 50% efficiency. This modest benefit is also partly due to the fact the thermal-to-electric power conversion efficiency for the plant is already rather high at 45%. For a lower temperature fusion chamber, direction conversion would have a greater impact. Also, to maximize the potential benefits of direct conversion, target designs should be modified to maximize output in ions. The question of whether the added complexity and equipment needed for direct conversion is worth the increase in net pant efficiency will require a detailed conceptual design study including estimates for the cost for the magnets and power equipment.

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