Systems Modeling for a Laser-Driven IFE Power Plant using Direct Conversion

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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. This study examines the potential benefits of increased efficiency when the expanding plasma is inductively coupled to an external circuit allowing some of the ion energy to be directly converted to electricity. 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%.

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, \( \eta_{\text{net}} \), which increases with increasing laser efficiency, target gain and fusion-to-electric power conversion efficiency as indicated in equation (1).

\[
\eta_{\text{net}} = \eta_{\text{e}} \left[ 1 - \frac{1}{\eta_{\text{l}} \cdot G \cdot M \cdot \eta_{\text{c}}} \right] \tag{1}
\]

Where \( \eta_{\text{l}} \) = laser wall-plug efficiency, \( G \) = target gain, \( M \) = overall energy multiplication factor, \( \eta_{\text{e}} \) = power conversion efficiency.

For a typical design where the chamber coolant flows to heat exchangers and drives a steam or Brayton cycle, \( \eta_{\text{e}} \) is just the thermal-to-electric conversion efficiency. A possible approach to increasing \( \eta_{\text{e}} \) 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 first-wall design with liquid lithium breading blanket [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 $/kWt basis.

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

| Parameter                  | Value         |
|----------------------------|---------------|
| Laser 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 MW$_t$   |
| Conversion efficiency ($\eta_c$) | 45%      |
| Gross electric power ($P_g$) | 1231 MW$_e$ |
| Laser efficiency ($\eta_L$) | 10%           |
| Laser power ($P_L$)        | 231 MW$_e$    |
| Net electric power ($P_n$) | 1000 MW$_e$   |
| Net plant efficiency ($\eta_{net}$) | 36.5% |

The reference case laser 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 242 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 MW$_e$. Other key parameters are also listed.

3. Results
We use the cost of electricity (COE) as the figure of merit for evaluating design trade and sensitivity studies. The COE is simply the annual expenses to cover the plant capital investment, operating and maintenance divided by the annual net energy produced. The COE for the reference case point is 6.6 ¢/kWt,h.
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 that in this analysis the net electric power, $P_n$, and rep-rate are held constant. Therefore, as $\eta_L$ varies, the laser energy (and thus target gain) changes to keep $P_n$ fixed. Under these assumptions, the COE increases by 13% as $\eta_L$ decreases from 10% to 5%, and the COE decreases by 4% as $\eta_L$ increases to 15%.

If we hold driver energy, gain, yield and rep-rate constant as $\eta_L$ 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¢/kW$_{eh}$ (+30%). At 15%, $P_n = 1077$ MW$_e$, and COE = 6.1¢/kW$_{eh}$ (-7%). The author’s opinion, however, is that it is best to compare results for a fixed net electric power, since that is the product of the power plant.

![Figure 1. COE versus laser efficiency. Net power is fixed at 1000 MW$_e$.](image1)

![Figure 2. COE versus power conversion efficiency. Net power is fixed at 1000 MW$_e$.](image2)

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 $\eta_L$ varies. As seen, power conversion efficiency has a significant impact on COE, particularly if it is reduce from 45%. At $\eta_c = 30\%$, the COE is 20% higher, while at $\eta_c = 60\%$, 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 $\eta_c$. 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.

3.2. Power plant using direct conversion

Direct conversion allows the 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 $\eta_c$ is substituted in equation (1).

$$\eta = \frac{f_i \cdot \eta_i + (1 - f_i) \cdot P_n + f_i \cdot (1 - \eta_i) \cdot M}{M} \cdot \eta_t$$

where $f_i = $ fraction of target yield in ions, $\eta_i = $ ion-to-electric conversion efficiency, $M_n = $ neutron energy multiplication factor, $M = $ overall energy multiplication factor, and $\eta_t = $ thermal-to-electric conversion efficiency.
Equation (3) assumes that the ion energy that is not directly converted, \( f_i(1-\eta_i) \), is available for thermal conversion as the same efficiency (\( \eta_t \)) 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 shows the power conversion and net plant efficiency as a function of \( \eta_i \) using the base case \( \eta_t = 0.45 \). If the ions can be converted directly at 50%, \( \eta_c \) increases from 45% to 51%, and the net plant efficiency (\( \eta_{net} \)) increases from 36.5% to 42.4%.

Figure 6 shows the impact on the COE for different assumptions. The solid curve assumes \( P_n \) is fixed at 1000 MW, and the rep-rate is held constant at 10 Hz, while \( E \) and \( G \) vary as \( \eta_i \) 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 \( \eta_i \) increases. In this case, the COE decreases by 11% for \( \eta_i = 50\% \).
4. Conclusions and Recommendations

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 limited. For the constant net power case, the COE is only reduced by ~5% if the ions are converted at 50% efficiency. If net power is allowed to increase with net efficiency, the COE is reduced by 11%. This modest benefit is also partly due to the fact the thermal-to-electric power conversion efficiency for the base case plant is already rather high at 45%. These results should be considered as a rough estimate of the potential benefits of direct conversion since we have assumed that the cost for direct conversion is equal to the cost of thermal conversion. The next step should be to carry out a more detailed conceptual design study of a direct conversion power plant including determination of the added costs (e.g., for magnets and direct conversion electrical equipment), cost savings in the thermal-to-electric part of the plant, and the impact on operation and maintenance costs. To maximize the potential benefits of direct conversion, the study should include target designs that maximize output in ions.

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