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Staging Rankine Cycles Using Ammonia for OTEC Power Production

D. Bharathan

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Table of Contents

List of Figures

List of Tables

Introduction

Recent focus on renewable power production has renewed interest in looking into Ocean thermal energy conversion (OTEC) systems. Early studies in OTEC applicability indicate that the Island of Hawaii offers a potential market for a nominal 40-MW_e system. However, a 40-MW system represents a large leap in the current state of OTEC technology with the associated risks, considering that the largest net-power producing system was tested at a power level of only 200 kW_e in the 1990s [Bharathan 1990]. Smaller sized plants on the order of 1 to 2 MW_e should be pursued first. Lockheed Martin Inc., under US Navy funding, is currently developing a 10-MW_e system design [Lockheed 2009]. With estimated capital cost per capacity ranging from 10,000$/$kW_e$ to 15,000$/$kW_e$ [Vega 2003] or more, it is essential that the potential risks associated with the first-of-the-kind plant be minimized. Every means for cost reduction must also be pursued without adding potential risks. Considering that majority of the costs are associated with the seawater systems, maximum use of the resource water takes on a high-importance. It is with this in mind that we take on this short study to assess the potential for increasing return on the investment both in terms of effective use of the seawater and of reducing equipment costs.

Approach

Many potential thermodynamic cycles have been investigated with the aim of reducing the overall cost for OTEC. Those include the familiar Rankine cycle, the open or Claude cycle, and others, such as mist-lift cycle [Ridgeway 1980], Kalina cycle [Kalina 1984] and Uehara [Uehara 1999] cycle, among others. On account its well-established practice in the engineering community we confine our analyses to the closed Rankine cycle at this time.

With respect to the working fluid, ammonia remains the fluid of choice for OTEC closed-cycle systems, even though other fluids such as propylene and various refrigerants have been looked into in the literature. We analyze power systems that use ammonia as the working fluid. At OTEC conditions, there is considerable amount experimental data available for heat exchangers that use ammonia and seawater, both for boiling and condensation [see for example, Panchal 1981]. Studies have also addressed qualification of aluminum alloys and methods for mitigation of biofouling [Panchal 1990].

Having made these practical and less-risky choices of ammonia and Rankine cycle, options to increase power yield from the seawater resources come in the form of staging the cycles. Staging allows maximum potential extraction of heat and power from a set of given resources. Many researchers have studied staging power cycles.

Figure 1 illustrates the nature of staging. A temperature-entropy (T-S) diagram shows both a single-stage and a two-stage Carnot cycles. Advantages of staging is best illustrated with Carnot cycles, without any loss of applicability. Both cooling and heating lines for the warm and cold seawater are indicated in this figure. The single stage working fluid state points are indicated by points ABCD. The area within this rectangle represents the amount of power that can be generated from that cycle. The temperature approach at points A and C are dictated by the minimal internal temperature approach (MITA) on the evaporator and condenser, respectively. If the cycle is staged as two separate cycles, indicated by the rectangles, AFJK and GHCI, one can still maintain the same temperature approach in the two evaporators and condensers. However, the overall area covered by these two rectangles is substantially greater than the for the single-stage cycle. It is possible to increase the number of stages to increase power yield from a given set of resources while maintaining a given set of approach temperatures. However, cost tradeoffs will limit the number of stages that can be economically used.

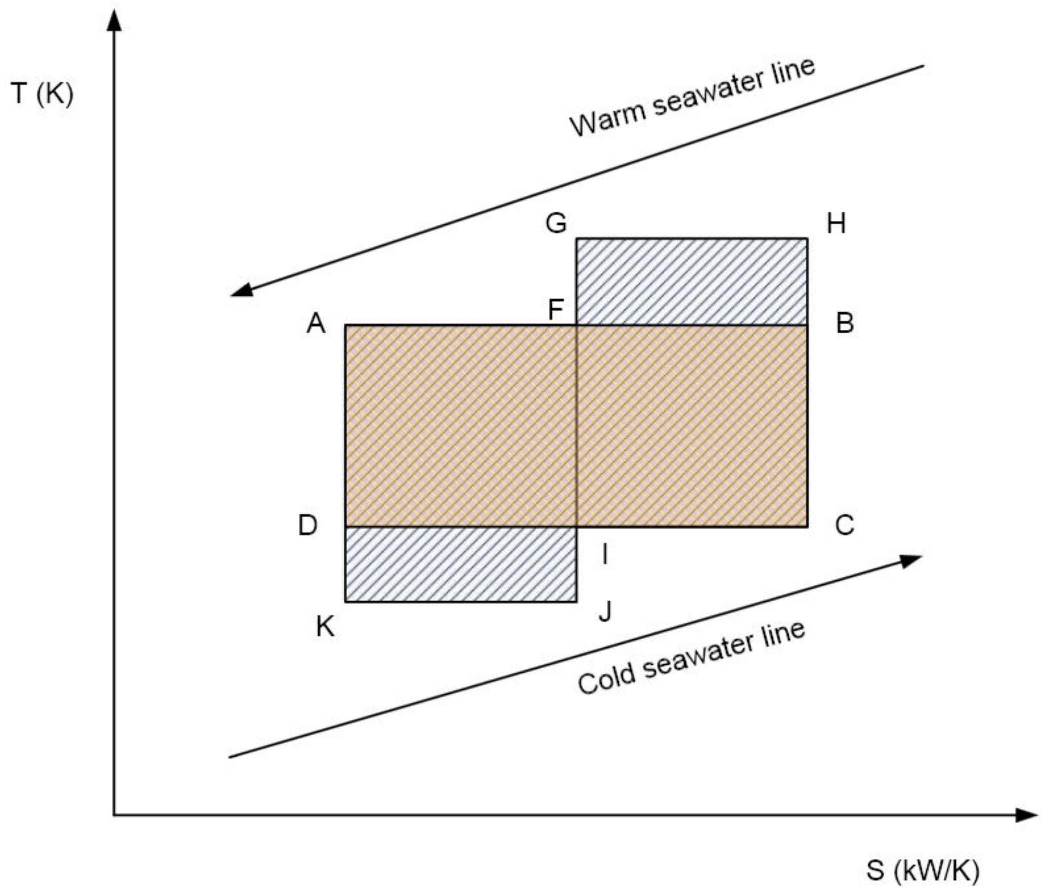

Figure 1 Cycle temperature-entropy (T-S) diagram for a single and two-staged Carnot cycles (not to scale)

While Figure 1 illustrates the principle for staging for Carnot cycles, the same arguments apply for the Rankine cycle as well.

Baseline plant

For the baseline plant, which was sized at a nominal 10 MW_e net electrical power, we used a warm seawater flow rate of 50,000 kg/s and a cold seawater flow rate of 28,450 kg/s. Economic analyses indicate that because of the larger costs and pumping power requirements for the cold seawater, a proportionately higher flow rate of warm seawater is beneficial [Vega 1995]. Other assumptions, based on many prior design studies, made for the rest of the presented analyses are summarized in Table 1. Once again, since cold seawater is a more costly resource, the condenser minimum internal temperature approach (MITA) is set at 1^{o}C as opposed to 1.2^{o}C for the evaporator. Condenser and evaporator pressure losses are based on earlier studies. Overall system loss is consistent with a floating platform for the plant.

OTEC staged nominal 10 MW system		
Assumptions		
Resource conditions	Value	Units
Warm water temperature	26	(°C)
Flow rate	50000	(kg/s)
Cold water temperature	4.5	(oC)
Flow rate	28450	(kg/s)
Working fluid	NH3	(---)
Efficiencies		
Water pumps	0.72	(---)
Working fluid pumps	0.72	(---)
Power turbine	0.75	(---)
Generator	0.94	(---)
Heat exchanger minimum approach temperature		
Evaporators	1.2	(°C)
Condenser	1.0	(°C)
Overall system hydraulics		
Warm water loop loss	0.3	(bar)
Cold water loop loss	0.72	(bar)
Evaporator loss/stage	0.06	(bar)
Condenser loss/stage	0.06	(bar)

Table 1 Summary of parameters for the baseline 10 MW_e OTEC plant

All components of the system were modeled using commercially available software ASPEN Plus [Aspen 2010]. Ammonia flow rate and the evaporator and condenser pressures were varied to arrive at maximum power production for the system. Figure 2 shows the details of the simulation for a single-stage power plant.

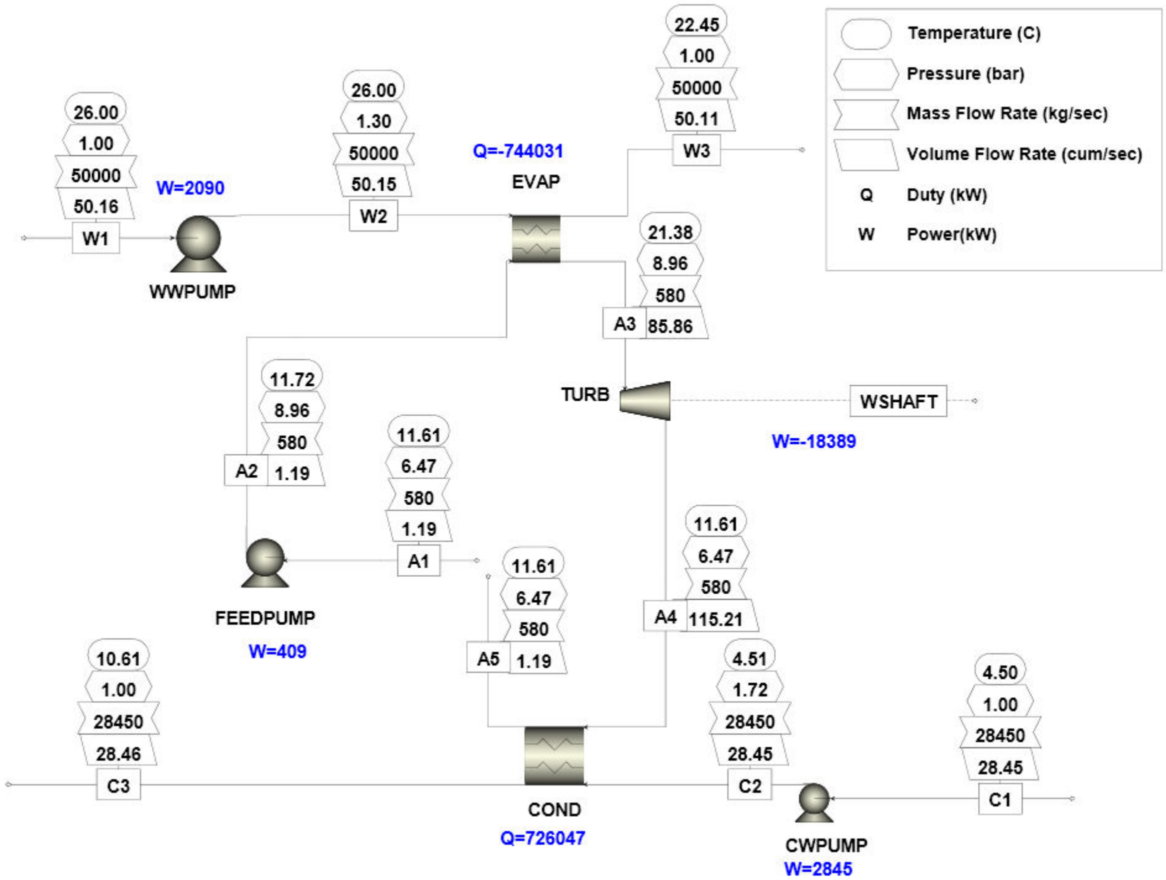

Figure 2 Detailed flow conditions for a single-stage 10 MWe plant

Optimization of the ammonia flow through the system indicates a peak net power yield of 11930 kW_e, at an ammonia circulation rate of about 585 kg/s. A plot of net power versus ammonia flow rate is shown in Figure 3. Despite the peak we note that in Figure 3, this peak is very shallow with the variation in the power of only about 100 kWe over the flow rate variation of about 15%. The system is very tolerant to variations in ammonia flow rate.

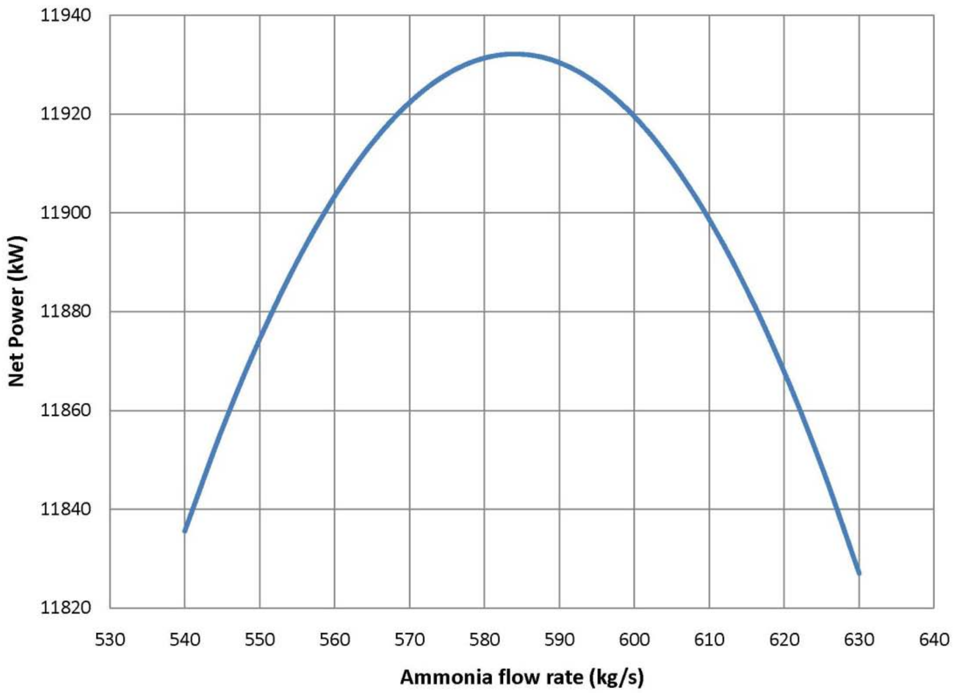

Figure 3 Variation of net power versus ammonia circulation rate

Note that the parasitic power used in the system is large, over 30% of the gross electric power generated as shown in Table 2. The quoted pressure losses in Table 1 are consistent with an OTEC system mounted on a floating platform. Over 5 MW_e power is used up in pumping the seawaters and circulating ammonia through the system. In case of a shore-based system, the parasitic power used within the plant may reach 40% of the gross power.

Temperature-entropy diagram for the single-stage ammonia cycle with proper scales is shown in Figure 4. Note that the warm seawater water leaves the system at 22.62°C and the cold seawater leaves at 10.3°C. There is still substantive potential left in these streams to extract usable energy using multiple stages in the cycle.

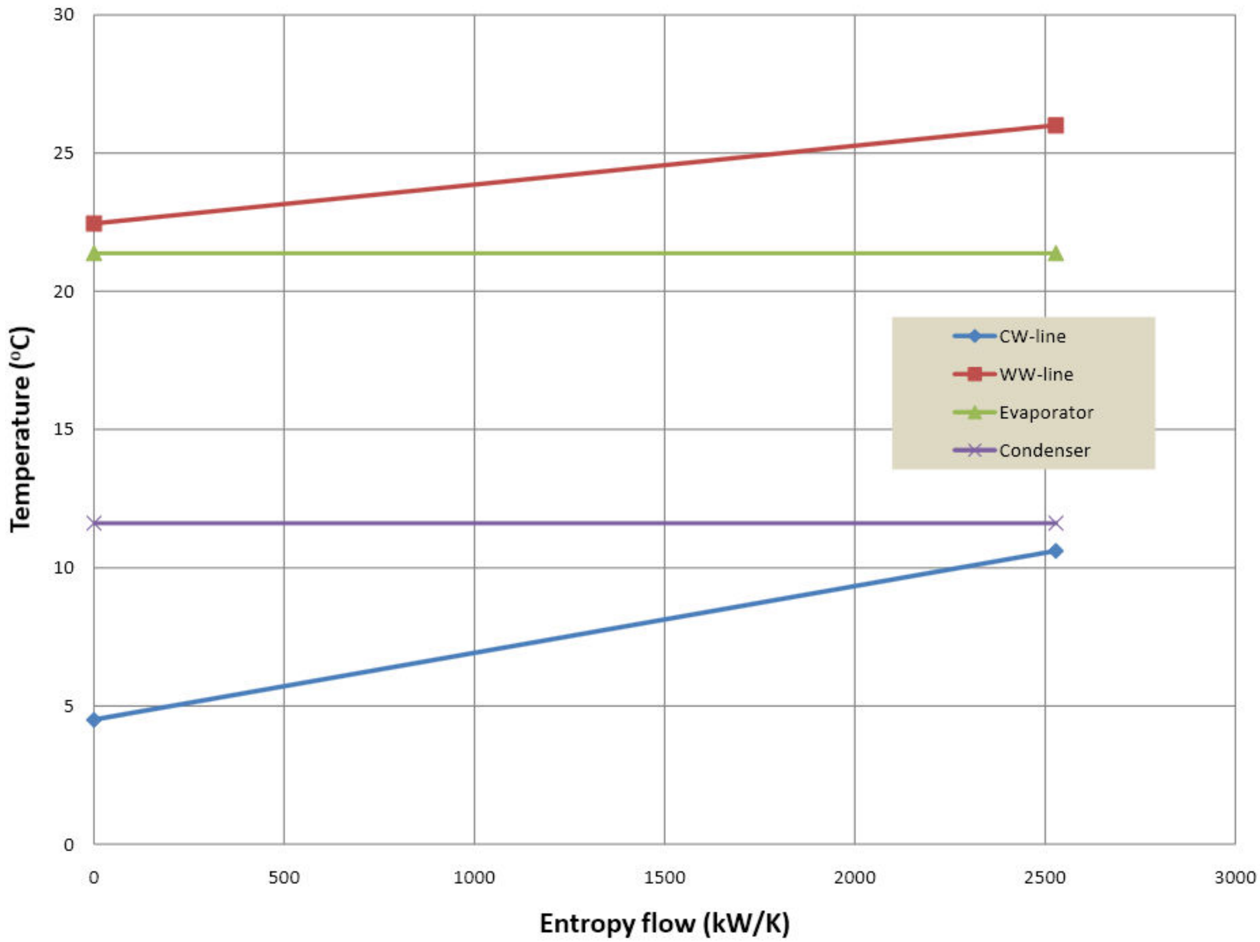

Figure 4 Temperature/entropy diagram for the single-stage ammonia OTEC power plant

Staged Power Plants

Consider a two-stage Rankine cycle system for OTEC as shown in Figure 5. This system still maintains the same MITA as the single-stage system. Flow rates of ammonia through the two stages were optimized to yield the results shown in this figure. Ammonia flow rates turned out to be the same for both the stages at 390 kg/s.

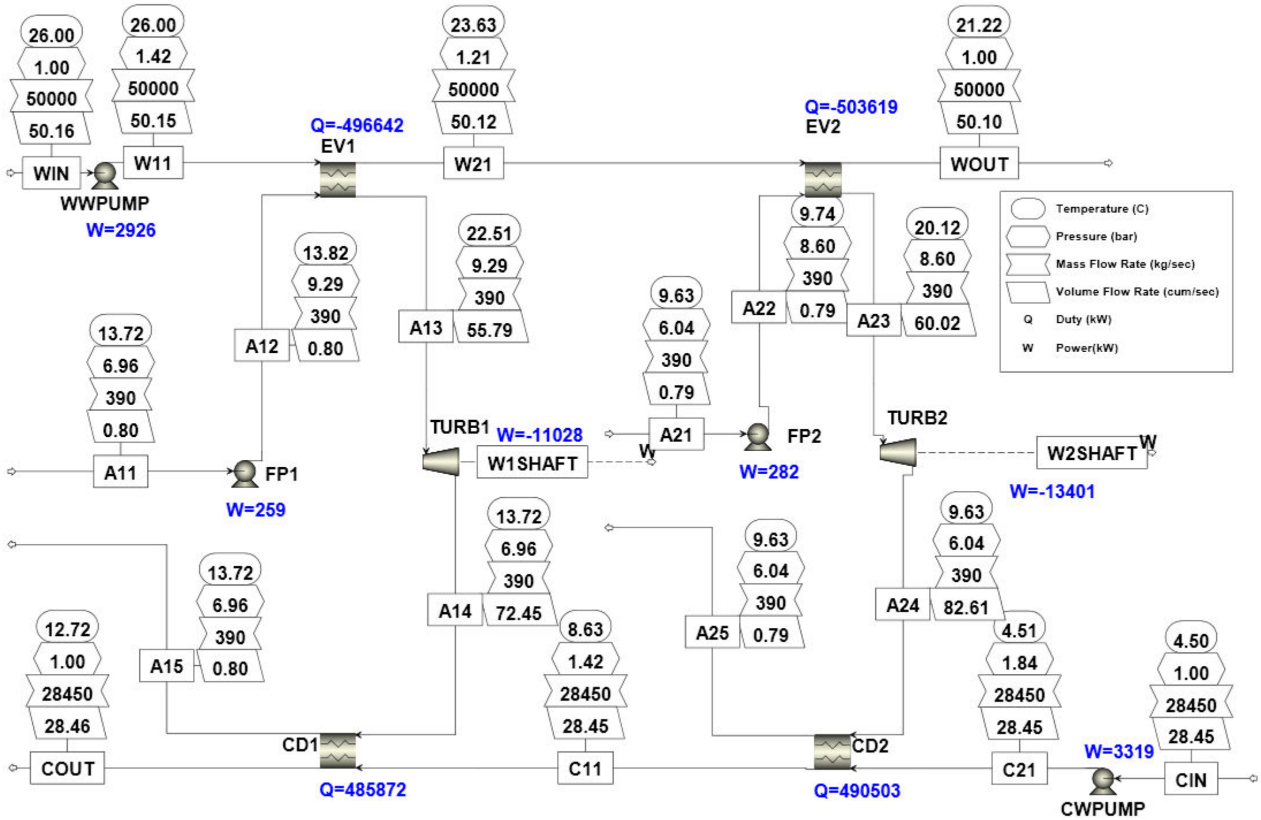

Figure 5 Two-stage Rankine cycle power plant showing details of the streams

The two stages produce a combined gross shaft power of 24.4 MW or electrical power of nearly 23 MW_e. This gross power is substantially greater than that for the single stage. Parasitic power for the system also increases on account of the two heat exchangers through which the seawaters must flow. Despite increased parasitic power, we calculate the net power for the two stage system to be 16.17 MW_e. This is substantially greater than that for the single stage system. We also note that the warm seawater leaves the system colder and the cold seawater warmer, than the single-stage system.

Heat exchanger requirements are also indicated in Table 2 in the form of an overall heat-transfer coefficient times the heat exchanger area product, or the (UA) product. Heat exchange area required for the two stage system is greater than that for the single stage.

We conducted a similar set of analyses for a three-stage and four-stage Rankine power cycles for OTEC. We summarize the results in accompanying Table 2.

Power system summary					
Number of stages	Units	1	2	3	4
Description					
Turbine shaft power	(kW)	18390	24426	26412	27185
Generated gross electrical power	(kW)	17287	22960	24827	25554
Parasitic power consumption					
Warm water pump	(kW)	2090	2926	3344	3762
Cold water pump	(kW)	2845	3319	3556	3793
Ammonia feed pump(s)	(kW)	420	541	585	602
Total parasitic power	(kW)	5355	6786	7485	8157
Net available power	(kW)	11932	16174	17342	17397
Percent increase (from single stage)	(---)	0	36	45	46
Optimum ammonia flow rate (per stage)	(kg/s)	580	390	350	300
	(kg/s)		390	350	300
	(kg/s)			350	300
	(kg/s)				300
Evaporator (UA)	(MW/K)	289	456	639	768
Condenser (UA)	(MW/K)	233	388	549	680
Warm seawater discharge temperature	(^{o}C)	22.44	21.22	19.60	18.70
Cold seawater discharge temperature	(^{o}C)	10.61	12.72	15.55	17.13

Table 2 Power system summary for staged OTEC cycles

Figure 6 plots the gross, net and parasitic power(s) for the staged systems. The gross, net and parasitic powers increase with increasing number of stages. The net power levels off between 3 and 4 stages. Most increase in net power is achieved by going from one to two stages.

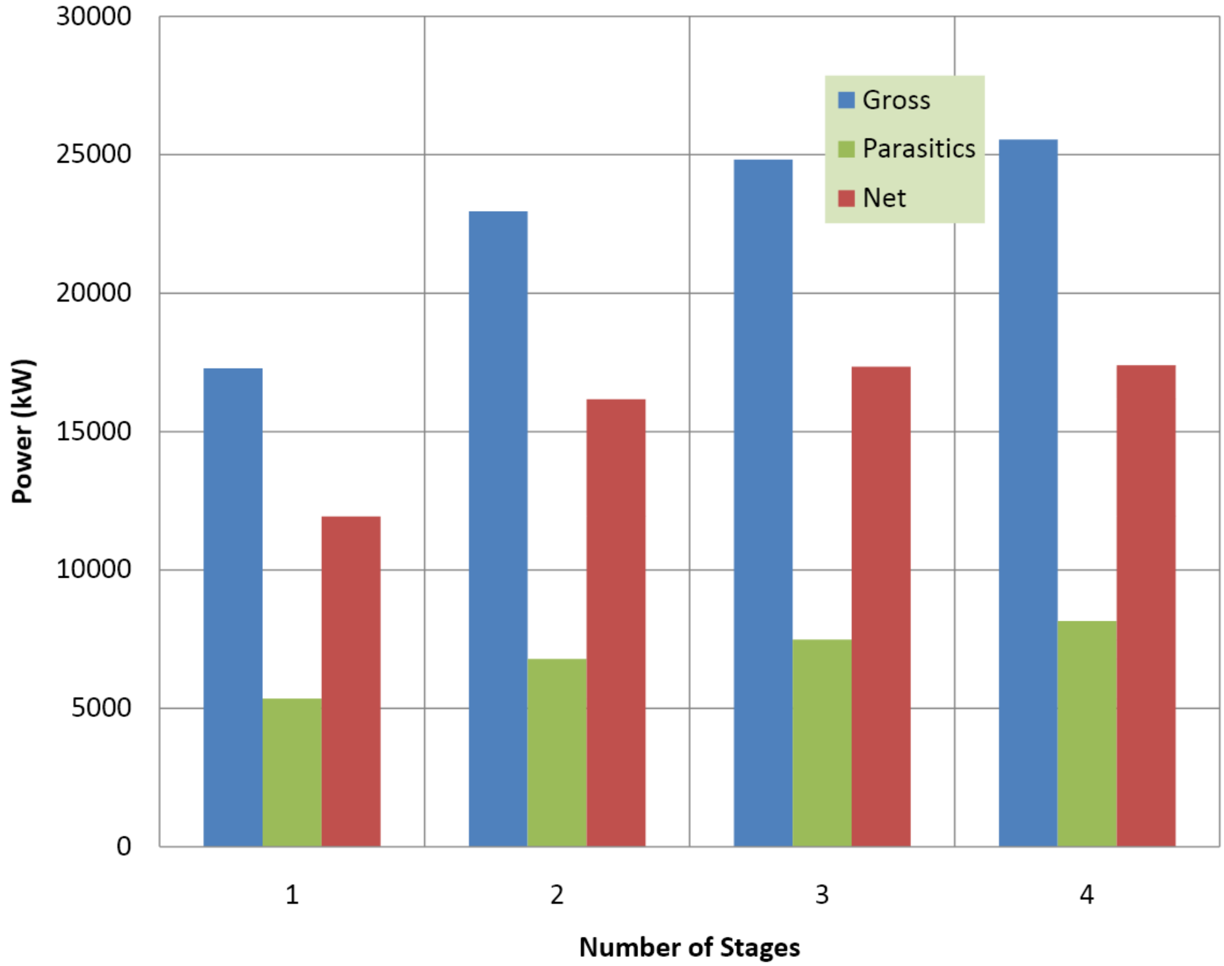

Figure 6 Variation of gross, net and parasitic powers with the number of stages

Required heat transfer areas for the various staged cycles are indicated in Figure 7. Heat transfer product (UA) increases more or less linearly with increasing number of stages. Condenser area is about 12% smaller than that for the evaporator in all cases. Heat exchanger costs are the next highest, after the cold seawater system. It is essential to limit these costs as well, which in turn will limit the number of applicable stages for economic operation.

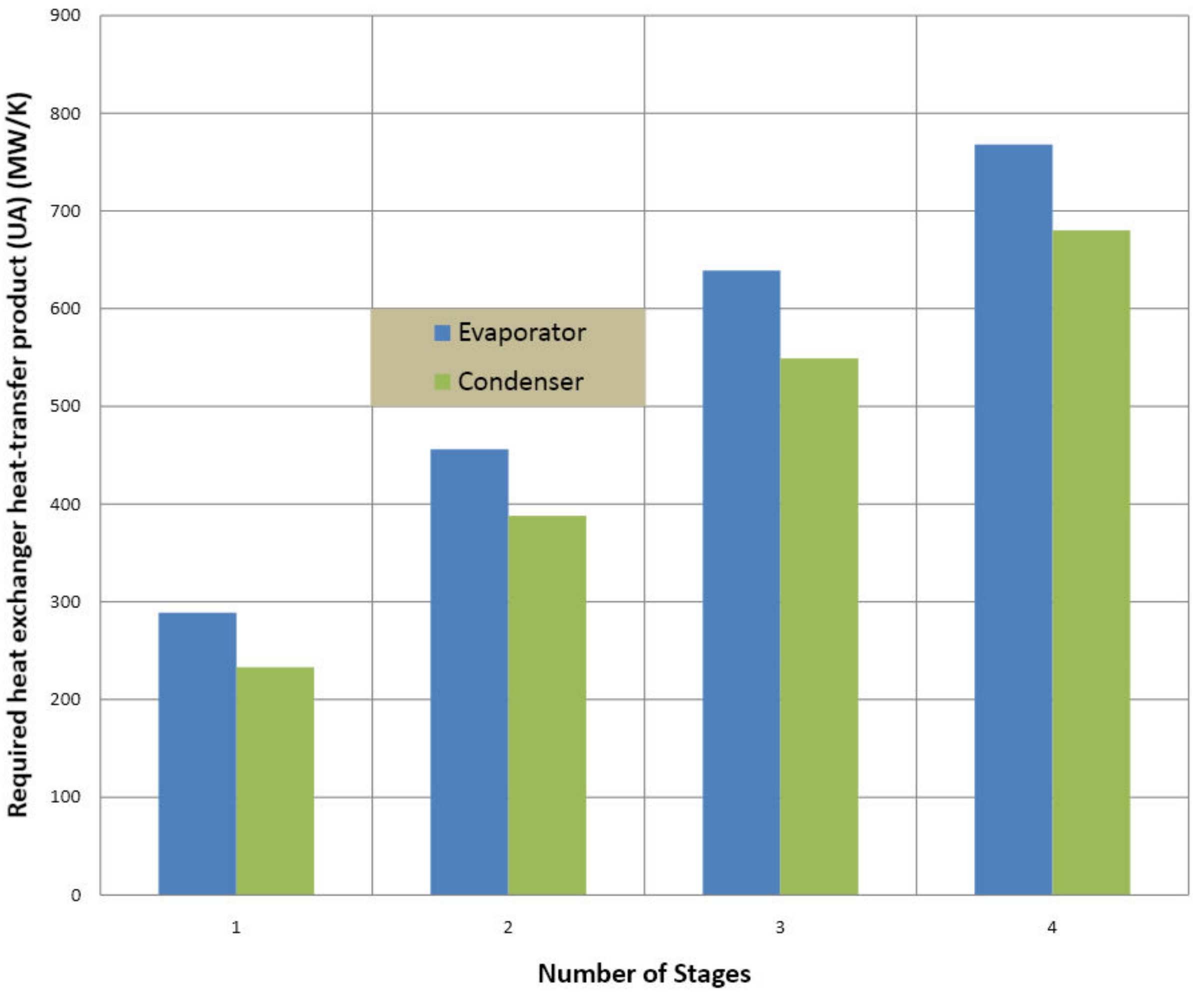

Figure 7 Variation of heat exchanger (UA) product requirements with the number of stages

Concluding remarks

Increased number of stages makes better use of the seawater resource and yields higher net power. The increase in net power decreases with increasing number of stages. However, the required heat exchanger area also increases, in this case more or less linearly, with increasing number of stages. Considering that the cold seawater system remains the highest cost item for OTEC, economic optimization will lead to two or perhaps three as the preferred number of stages for the closed cycle OTEC system. The author recommends a similar study with other potential working fluids, such as, propylene.

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