Exergo economic analysis of solar-assisted hybrid power generation systems integrated with thermochemical fuel conversion

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HIGHLIGHTS

- Solar-assisted hybrid power systems integrated with thermochemical fuel conversion.
- Solar-fuel hybrids for efficient use of lower temperature solar heat for power generation.
- An equation to determine the exergo-economic competitiveness of such hybrid systems.
- Effects of carbon tax, value of byproducts and hybridization cost on electricity cost.
- Exergo-economic analysis simplifies cost competitiveness evaluation of the hybrid systems.

ABSTRACT

Solar-assisted hybrid power generation systems integrated with thermochemical fuel conversion are of increasing interest because they offer efficient use of lower temperature solar heat, with the important associated advantages of lower emissions, reduction of use of depletable fuels, production of easily storable fuel to alleviate the variability of solar heat, and relatively low cost of the use of lower temperature solar components. This paper examines economic performance of two previously proposed and analyzed thermochemical hybridized power generation systems: SOLRGT that incorporates reforming of methane, and SOLRMCC that incorporates methanol decomposition, both of which use low temperature solar heat (at ≤220 °C) to help convert the methane or methanol input to syngas, which is then burned for power generation. The solar heat is used “indirectly” in the methane reforming process, to vaporize the needed water for it, while it is used directly in the methanol decomposition process since methanol decomposition requires lower temperatures than methane reforming. This analysis resulted in an equation for each power system for determining the conditions under which the hybrid systems will have a lower levelized electricity cost, and how it will change as a function of the fuel price, carbon tax rate, and the cost of the collection equipment needed for the additional heat source.

1. Introduction

Most thermal power generation systems (e.g. fossil fuel, nuclear, solar, geothermal) use a single source of heat at a single temperature, and also use that heat source directly as heat. In cases where the cost of the heat is related to the temperature, such as with solar heat collection equipment, or when the temperature of the heat source is limited by operational considerations, such as in nuclear reactors, or when the available temperature is well below the material endurance temperature, such as in geothermal heat sources, or when it is desired to employ renewable or other types of energy that reduces global warming gas emissions or/and reduces use of depletable fuels, or when waste heat at appropriate temperatures and price is available, such as in compounded internal combustion engines, it was found that gains in efficiency and reduction of emissions and cost could be achieved by power systems using multiple heat sources of different temperatures, which are called here “hybrid” systems.

Early work on hybrid power cycles was done by Lior and co-workers [1–5] who have analyzed and developed hybrid solar-powered/fuel assisted steam cycles and performed experiments with one of them (22.4 kW output), a concept similar to the one that was later (in the 1980s) used by the Luz company for the construction and successful operation of 9 solar-thermal power plants (SEGS) generating about 354 MWe (net) in southern California [6–8], that still operate competitively. The concept is successful because it uses solar energy at the lower temperature level, where
it is more economical, and augments it by smaller amount of heat from fuel combustion to: (1) raise the cycle temperature and thus efficiency, and (2) allow fuel heat backup when solar energy is not sufficiently available, without having to increase the number of collectors and thermal storage capacity. Furthermore, proper configuration of the systems’ heat donors and receivers offers a closer match between their temperatures (smaller temperature differences between donors and receivers) and thus lower exergy losses.

Different from the typical thermal hybrid systems that may involve chemical reactions in the heat addition process only, if fuel combustion is used, thermochemical hybrid systems are designed to include chemical reactions, typically to convert some hydrocarbon to readily-usable fuel, altogether to result in a more efficient and less polluting power generation system. In this type of system, lower temperature heat, such as solar, geothermal, or waste, is converted by such chemical reactions to the chemical exergy of the ultimately-combusted fuel (such as syngas). Compared with thermal hybridization, thermochemical hybridization can have also the advantage that it can allow conversion of the exergy of intermittent heat sources (such as solar) to much higher fuel chemical exergy that is therefore much easier to store and transport than the energy/exergy of such input heat sources. Furthermore, low/mid temperature solar heat (~200 °C) is high enough to be used by a syngas-producing reforming process, thus potentially reducing the total cost relative to conventional solar thermal power plants that necessarily use more expensive solar collection equipment due to their higher solar temperatures.

While thermochemical hybrid power cycles using multiple sources may have thermodynamic performance advantages over conventional single heat source power generation systems, it is of course important to assess also their economic viability. Usually there is a trade-off between the performance and cost of equipment in a system, e.g., in heat exchangers exergy destruction decreases with the reduction of the temperature difference between the cold and hot streams, but the latter requires larger heat exchange area and heat transfer coefficient and thus incurs higher cost.

Another important economic consideration is the potential for saving depletable fuel and reducing emissions (including of greenhouse gases) by hybrid power systems using renewable heat sources or other heat sources that generate no emissions, both features having important economic impact when considering the rise of the fuel price and carbon tax (or other monetary penalty for CO2 emissions).

Comprehensive work has been done on thermochemical hybrid system and many systems have been proposed and analyzed (reviewed in [91]), but none have been found using an exergo economic analysis method to analyze the economic performance of this type of system. The main objective and novel contribution of this study is to evaluate the economic performance of thermochemical hybrid power generation systems, by using the exergo
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