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A MultiObjective Genetic Algorithm Framework for electricity / hydrogen co-production from generation IV nuclear energy systems

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Abstract

One of the great motivations of studying and developing Generation IV (Gen IV) reactors of VHTR (Very High Temperature Reactor) design is their capacity to efficiently produce both electricity and H₂ (hydrogen). This study aims at developing an optimization methodology for cogeneration systems of hydrogen and electricity, with respect to energy constraints, economics and conjuncture in terms of demand. It lies within the scope of a collaboration between the Laboratoire de Génie Chimique (LGC Toulouse, France) and the French Atomic Energy Commission (CEA, Cadarache, France) in order to compare various cogeneration systems from both energy and economics viewpoints. This paper describes the different steps of the technico-economic methodology for H₂ and electricity cogeneration systems.

Keywords: Hydrogen, Electricity, cogeneration, Gen IV nuclear systems, multiobjective optimization

1. Introduction

Hydrogen is currently viewed as one of the energetic vectors that will replace traditional fossil fuels in the XXIth century. Although the transition is assumed to be progressive, innovative technologies for a massive production of H₂ have to be investigated.

The VHTR (Very High Temperature Reactor) concept, considered as the nearest-term reactor design, can indeed be coupled on the one hand, with innovative electricity-generating cycles and, on the other hand, with massive H₂ production processes. Thus, due to a high exit core temperature (at least 950°C) reached by helium used for cooling, VHTR is dedicated to the cogeneration of electricity and hydrogen by Sulphur-Iodine (S-I) thermochemical cycle or by High Temperature Electrolysis of steam water. Globally, these processes require the simultaneous supply of electricity and heat at high temperature. The optimal design of these process configurations constitutes an important challenge.

In this perspective, simulation tools for thermal systems were previously developed by the CEA (French Atomic Energy Commission, Cadarache, France), i.e., CYCLOP for thermodynamic cycle modelling. This code allows to model innovative energy production systems for given operating conditions while taking into account the influence of classical variables: exchanger efficiency, pressure ratio and isentropic efficiency (compressor, turbines ...), pressure loss...

This paper first describes the three steps of the technico-economic optimization methodology implemented for the selection of cogeneration systems. The first one is based on a bicriteria optimization with total life cost and exergy losses minimization. The second one implies exergetic production cost evaluation of any energy form. The last step provides decisional data, as hydrogen production cost for different scenarios for electric market corresponding to a given plant, to make possible the choice between different systems. Finally, the methodology is applied successfully to two different systems dedicated to electricity and hydrogen production, taking into account various scenarios of the electricity market.

2. Technico-economic optimization methodology for H₂ and electricity cogeneration

The choice of the best strategy for electricity and H₂ massive production systems is a technico-economic concern. The cogeneration system considered here (Fig. 1) consists in coupling a VHTR nuclear reactor with an electrical generator (that is a Brayton cycle) in direct cycle, on the one hand, and, with a hydrogen production plant (Iodine-Sulphur cycle) for which the thermal and electrical demand is known.

It involves a site of 4 autonomous sections, each one including a VHTR reactor, an electrical generator and n H₂ production plants operating in parallel.

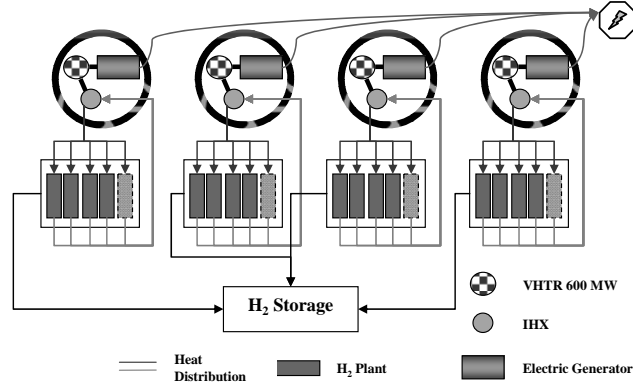


Fig. 1. Configuration of electricity and H₂ cogeneration site (example)

2.1. Bicriteria optimization by exergetic losses and lifespan cost minimization of the production plant

The first step of the methodology implies a bicriteria optimization, by simultaneous minimization of the total exergetic losses and of the total costs of the production sites over their lifespan.

The choice of a criterion based on the minimization of the exergetic losses was justified in [1]: it represents the lost “available work” during the energy conversion. The thermodynamic model of the cogeneration system is implemented in the CYCLOP simulator [2]. The economic criterion takes into account both construction costs of the site (nuclear reactors, electricity generators, H₂ plants) and operating costs (nuclear fuel, maintenance of VHTR and H₂ plants) for 60 years life (Eqn. 1):

$$TC_{\text{Site}} = \sum_{t=1}^D [Ca_{\text{Nucl.Fuel}}(t) + Ca_{\text{O\&M}}(t) + Ca_{\text{Invest}}(t)] \times (1+i)^{-t} \quad (\text{Eqn. 1.})$$

Where:

TC_{Site} : Total Cost (M€), $Ca_{\text{Nucl.Fuel}}$: nuclear fuel annual cost, $Ca_{\text{O\&M}}$: operating & maintenance costs, Ca_{Invest} : investment annual cost (including end of life costs), i : discount rate (%), D : Cogeneration Site Life (years)

The economic model, based on the so-called SEMER code [3], was extended for H₂/electricity cogeneration case and cost models for innovative components were also developed specifically. The multiobjective optimization procedure was performed via genetic algorithms, that have proven to be particularly well-fitted for such problems and have the advantage to lead directly to the so-called Pareto front. The bicriteria optimization step was carried out with MULTIGEN library [4], as a master procedure, connected to CYCLOP and SEMER codes (Fig. 2).

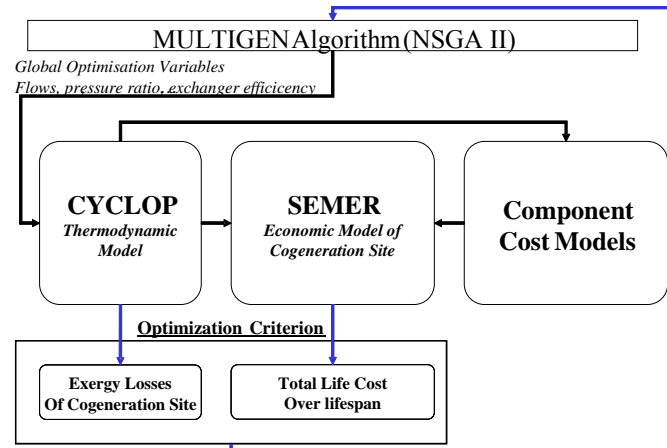


Fig. 2. Integration of the different models in the methodology

Typical results are presented in Fig. 3 and exhibit different sets of compromise solutions, called Pareto fronts corresponding to various H₂ production levels represented by one or several H₂ production plants. The objective of the following step of the methodology is to reduce this set to assist the decision maker in selecting the preferred or best compromise solution from among the whole set of solutions.

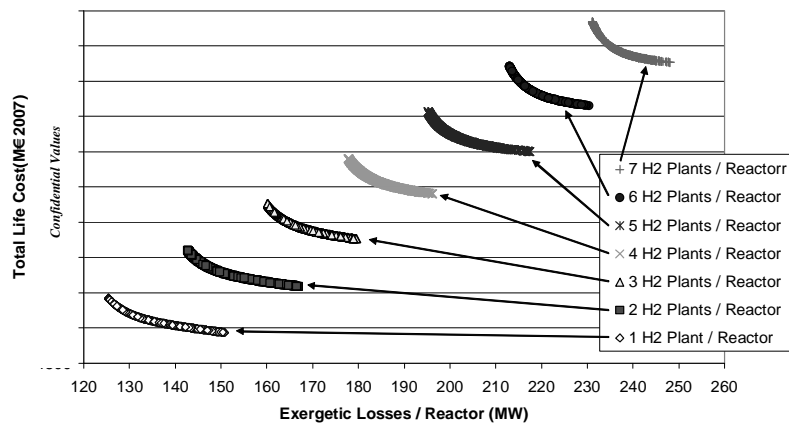


Fig. 3. Bicriteria optimization results: Pareto fronts for cogeneration systems.

2.2. Global production cost evaluation

The production cost evaluation is classical for electricity production (Eqn. 2), and has been performed for the solutions identified at the first step of the methodology (Fig. 3).

$$C_{Prod} (\text{€ / kWh}) = \frac{TC_{Site}}{\sum_{t=1}^D \left[\frac{Pa(t)}{1000} (1+i)^{-t} \right]} \quad (\text{Eqn. 2.})$$

Where:

C_{Prod} : production cost (€/kWh), Pa : annual production of energy (MWh/year).
For cogeneration systems, the annual production of energy involves the contribution of both electricity and exergetic power of H_2 :

$$Pa = H \times [W_{elec} + \dot{m}_{H_2} \times P_{Ex}(H_2)] \quad (\text{Eqn. 3.})$$

Where:

H : production period (hours/year), W_{elec} : electric production (MW),
 \dot{m}_{H_2} : H_2 production (mol/s), P_{Ex} : Exergetic Power of H_2 (235.3 MJ/mol).

Let us mention that the electrical and hydrogen production cost is identical in value (€/kWh) from an exergetic point of view. According to Fig. 4, solutions with minimum exergetic production costs can be highlighted: they correspond to minimal production costs of electricity. But, at this level, H_2 and electricity are undifferentiated from the production cost point of view.

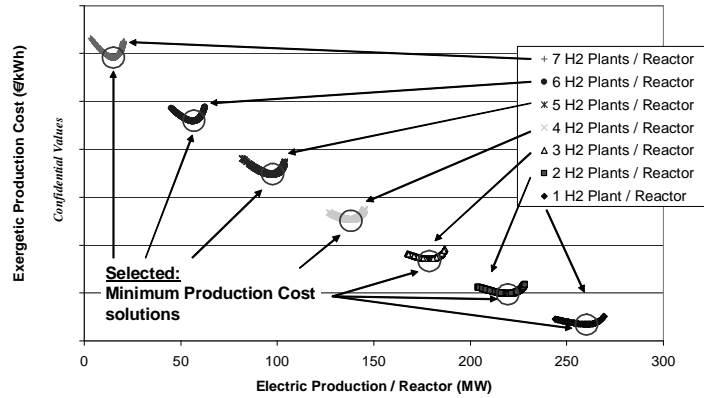


Fig. 4. Production cost evaluation for bicriteria optimization results

2.3. Fixing the cost of electricity

As abovementioned, the use of the exergy concept implies that the production costs of both forms of energy are undifferentiated, i.e. the overcost related to the production of H_2 is reflected on the cost of electricity. The production cost of electricity (€/kWh) is then fixed to deduce the production cost of hydrogen (€/kg). For a given H_2 /electricity production ratio, an optimum of H_2 production costs exists for a given electricity cost, as displayed in Fig. 5. These results constitute a decisional map for the selection of cogeneration systems. Each

optimal solution is related to a simultaneous electricity/hydrogen production: optimal production costs can be deduced from Fig 5.

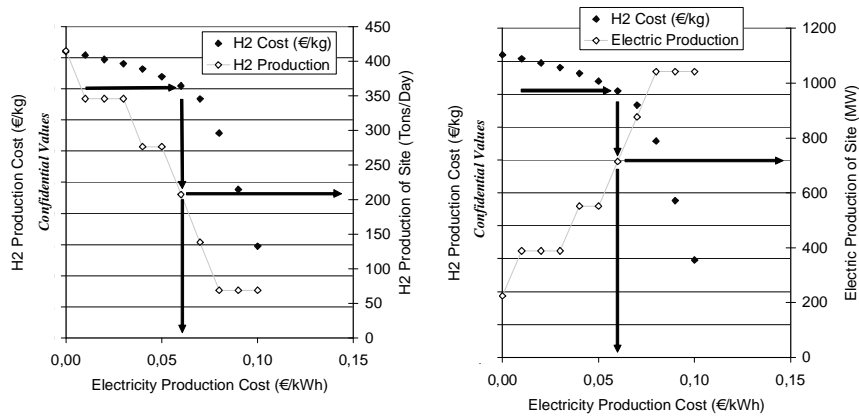


Fig.5. Final optimal cogeneration solutions for decision makers

3. Conclusions

The proposed methodology, based on classical evaluation criteria, makes it possible to visualize clearly and quickly the economic interest of cogeneration systems (electricity & H₂). From the application of exergetic theory, the overall production cost can be deduced. When fixing the cost of electricity, different scenarios can be proposed to the decision maker to assist him for cogeneration system selection. This methodology is intended to be applied to any system, implying different modes of production for electricity and hydrogen.

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