

Techno-economic study of hydrogen production by High Temperature Electrolysis coupled with an EPR, SFR or HTR – Water steam production and coupling possibilities

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Abstract

The potentialities of massive hydrogen production by High Temperature Electrolysis coupled with three nuclear reactors (the European Pressurized Reactor, the Sodium-cooled Fast Reactor and the Very High Temperature Reactor) were studied in terms of perspectives and costs. First, we present the features of producing water steam by using the three nuclear reactors. Secondly, we present the hydrogen production cost for the HTE process coupled with each type of nuclear reactor. This evaluation has been done by using a genetic algorithm procedure. High potentiality for these HTE couplings was assessed and the electricity price appeared as a key parameter in order to reach low hydrogen production costs.

Keywords: EPR, SFR, VHTR, hydrogen, nuclear, high temperature electrolysis

Nomenclature

A_v	Reactor availability, (%)
A_p	Operation time, (s/yr)
CTA	Hydrogen Production cost, (€/kg)
C_{p_i}	Heat capacity, (kJ/kg)
$C_{i,elec}$	Electrolyser investment cost, (€)
$C_{i,exch}$	Heat exchangers investment cost, (€)
$C_{o,elec}$	Electrolyser operation cost, (€/yr)
$C_{o,th}$	Thermal consumption as an operation cost, (€/yr)
$c_{i,elec}$	Unitary electrolyser investment cost, (€/kWh _e)
$c_{i,exch}$	Unitary heat exchangers investment cost, (€/m ²)
$c_{o,elec}$	Unitary electrolyser operation cost, (€/kWh _e)
$c_{o,th}$	Unitary thermal consumption cost, (€/kWh _{th})
H_t	Hydrogen production, (kg/yr)
j	Current density, (A/cm ²)
L_v	Vaporisation heat, kJ/kg
\dot{m}_i	Mass flow, (kg/s)
M_i	Molar Mass, (kg/kmol)
$P_{tot,useful}$	Electrolyser power for water dissociation, (kW)
P_1	Initial pressure, (MPa)
P_2	Final pressure, (MPa)
R	Ideal gas constant, 8.314 J mol ⁻¹ K ⁻¹
T_i	HTE construction time, (yr)
T_e	HTE exploitation time, (yr)
T_x	Temperature after mixing unit, (K)
$U_{electrolyser}$	Operating voltage of electrolyser, (V)
T_i	Temperature, (K)

Greek symbols

η	Hydrogen conversion efficiency, (%)
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τ	Discount rate, (%)
Subscripts	
1	Initial
2	Final
cs	Condensed steam
fw	Feed water
H ₂	Hydrogen
H ₂ O	Water
phst	Steam after mixer
e	Electric
steam2	Steam recycled for preheating
ref	reference
t	time, (yr)
th	Thermal
vap	vapour
water	water
x	mixer outlet stream

1. Introduction

Nowadays, hydrogen is essentially used in the chemical industry and it is mainly produced through Steam Methane Reforming (SMR), which is a high CO₂ emission process. Alternative massive hydrogen production processes are necessary to fulfil the hydrogen needs for industrial processes, especially petrochemical and refining, that would present an annual increase between 4% and 5%, for the next 20 years [1]. Moreover, hydrogen production needs would be amplified considering the raising applications of hydrogen as an energy carrier and other industrial processes as in the steel and cemetery industries. Several alternative processes for hydrogen production are being studied and results about nuclear reactors present a wide range of coupling possibilities for massive hydrogen production [2]. In this paper, we consider the coupling between three nuclear reactors (EPR, SFR and VHTR) and the High Temperature Electrolysis process (HTE).

No opened literature has been found about an EPR or a SFR coupled with the HTE process for hydrogen production. However, hydrogen production has been evaluated for other kind of nuclear reactors. Harvego et al. [3] studied the coupling of a Modular Helium Reactor (MHR) of 600 MW_{th} with the HTE process. They considered that 90% of the MHR heat (with a Brayton cycle) would serve to electricity production and 10% to steam generation. They studied the heat exchange between the secondary helium loop and a steam generator, avoiding all tritium transfer to the steam circuit. Verfondern and von Lensa [4] proposed the usage of a High Temperature Gas Reactor (HTGR) for a hydrogen European economy context. In last, Yildiz and Kazimi [5] studied several nuclear reactors and they proposed different nuclear applications depending on reactors type (figure 1). Regarding the CO₂ emissions, Utgikar and Thiesen [6] carried out a Life Cycle Assesment (LCA) of hydrogen production by HTE-nuclear coupling, using a VHTR of 600 MW_{th} with 45% efficiency, and they found that CO₂ emissions are smaller than almost any other hydrogen production process.

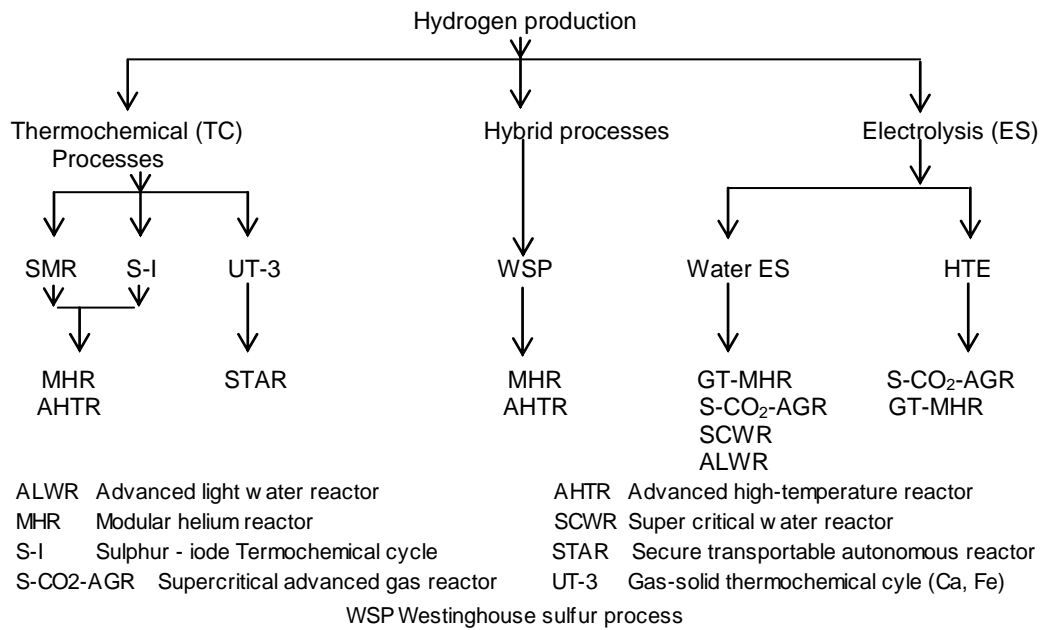


Fig 1. Technology options for nuclear hydrogen production [5].

This work basically deals with the water steam generation and electrolysis, for hydrogen production, by using three different nuclear reactors:

- the new European Pressurized Reactor (EPR), which produces water steam at low-medium temperatures, from 569 K to 603 K for the primary circuit at 15.5 MPa and from 503 K to 566 K for the secondary exchange circuit at 7.8 MPa [7]
- a Sodium-cooled Fast Reactor, which produces water steam up to 753 K at 12.2 MPa in the tertiary circuit [8].
- a Very High Temperature Reactor (VHTR), which works with helium up to 1200 K that can be used to produce water steam, under several hypotheses according to Rodriguez and Pinteaux [9], at temperatures up to 743 K and a pressure of 3 MPa.

In this work, we present in section 2 the water steam generation by nuclear reactors. Then the High Temperature Electrolysis process will be described in section 3 and in last, in section 4, the hydrogen production cost for HTE-nuclear reactor couplings will be detailed. For the hydrogen production units, a techno-economic study was carried out. An optimisation method, based on genetic algorithms was used to estimate the lowest hydrogen production cost for each configuration.

2. Hydrogen production by Nuclear-HTE coupling

2.1 Steam generation by using a European Pressurized Reactor

For the EPR, two possibilities to obtain water steam are proposed. First, the drawing off of water steam in the secondary circuit was evaluated in terms of possible impact in electricity production and reactor availability. Secondly, full water steam production with an EPR was considered, which means non-electricity production. The feed water is introduced to the secondary circuit, in which the steam generators are placed. Then the produced steam is sent to the high temperature electrolyser. For both options, current discussions about operation pressure could lead to propose a pressure drop in order to protect the high temperature electrolyser from damage. Even if specific pressure values have not been decided, in this study we propose an isenthalpic pressure drop from 7.8 MPa to 4.05 MPa, 3.04 MPa and 1.52 MPa.

2.1.1 Operating conditions of a European Pressurized Reactor.

Considering that the EPR is one of the 3rd generation Pressurized Water Reactors (PWR) [10], we considered the EPR design as a reference [7], and for further technical details we studied the PWR-1300 design [11]. These reactors have four loops composed by a primary circuit with water at high pressure conditions (~15.5 MPa) and a secondary circuit (7.8 MPa). In the primary and secondary circuit heat exchange zone, primary circuit temperatures are between ~568 K and 596 K. Heat is transferred to the secondary circuit with water at high pressure going from 6.0 MPa to 8.0 MPa and temperatures between 492 K to 569 K. The global efficiency for an EPR is expected to be 36% and its availability of 92%. Figure 2 shows the secondary circuit drawing off possibility.

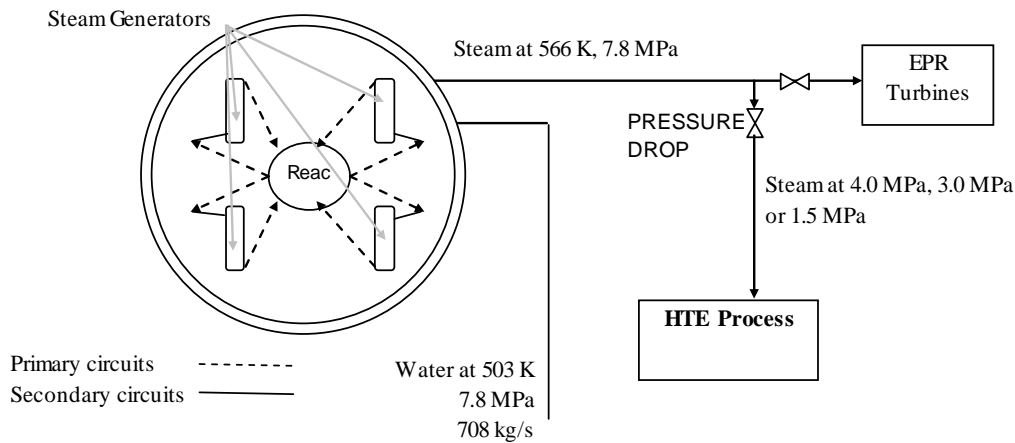


Fig 2. EPR secondary circuit drawing off schema.

2.1.2 Drawing off of water steam of the secondary circuit

Mass and energy balance have been carried out for one EPR loop, with capacity of 1125 MW_{th}. Considering the secondary circuit pressure of 7.8 MPa, three drawing off pressures were studied: 4.05, 3.04 and 1.52 MPa. We propose an isenthalpic pressure drop of water steam drawn off after the outlet of steam generator section. In this case, temperatures and possible liquid fraction (from slight steam condensation) are presented in Table 1.

Table 1. Properties of drawing off stream after pressure drop.

	<i>Pressure – Mpa</i>		
	4.05	3.04	1.52
<i>Outlet temperature - K</i>	523	506	471
<i>kg steam/(kg liquid + kg steam)</i>	0.978	0.978	0.986

Under a potentiality point of view, an EPR loop at 100% capacity exploitation would generate 708 kg/s of steam. Then based on the average of French reactors exploitation presented in ELECNUC [12], we estimated that an EPR working at 96.8% could produce electricity for the power grid (in which the average needs demand the 88.54% of the EPR capacity), and 1.23 kg/s of hydrogen per loop, at steam total conversion in the HTE process. This would lead to an annual hydrogen production, estimated by using equation (1), of 5.68×10^8 kg per reactor or ~7% of European hydrogen production. Moreover, the fact of fixing a nuclear exploitation, independently of electrical need peaks could allow EPR steady state exploitation and agree with the ideas exposed by Forsberg [2] about hydrogen production by steady state nuclear reactor operation.

$$H_t = \eta \times Av \times Ap \times \dot{m}_{H_2O} \left(\frac{M_{H_2}}{M_{H_2O}} \right) \quad (1)$$

2.1.3 Full steam production by a European Pressurized Reactor

The EPR, under construction [3], will have a total thermal capacity of 4500 MW_{th}. The steam production by reactor loop is 708 kg/s in secondary circuit, at 7.8 MPa. After steam generation, for hydrogen production, the turbine would be replaced by one water pre-heater. The pre-heater could allow the temperature increase of the feed fresh water at ambient temperature up to 503 K, which is the inlet temperature in the steam generators [7] (cf. figure 3.) Carrying out a mass and energy balance for the pre-heater/condenser and the stream mixer M1, solving equations (1-2), we observe that a water steam production of 468 kg/s could be reached. This water could represent, in a total steam conversion into hydrogen, a H₂ production of 50 kg/s per loop. The steam flow sent to the pre-heater would be of 240 kg/s, and the temperature before the pre-heater would be around 285 K. In this case, the power needed for steam electrolysis would be raised to 500 MW_e and a global annual hydrogen production, estimated for one reactor using equation (1), would be up to 5.8 x 10⁹ kg or ~72% of the European hydrogen production.

$$T_x = \frac{\dot{m}_{phst} Cp_{water} (T_1 - T_{ref}) - L_{vap} \dot{m}_{phst}}{\dot{m}_{steam2} Cp_{water}} + T_{ref} \quad (2)$$

$$T_x = \frac{(T_{fw} - T_{ref}) Cp_{vap} (\dot{m}_{steam2} - \dot{m}_{phst}) + (T_{cs} - T_{ref}) Cp_{water} \dot{m}_{phst}}{\dot{m}_{steam2} Cp_{water}} + T_{ref} \quad (3)$$

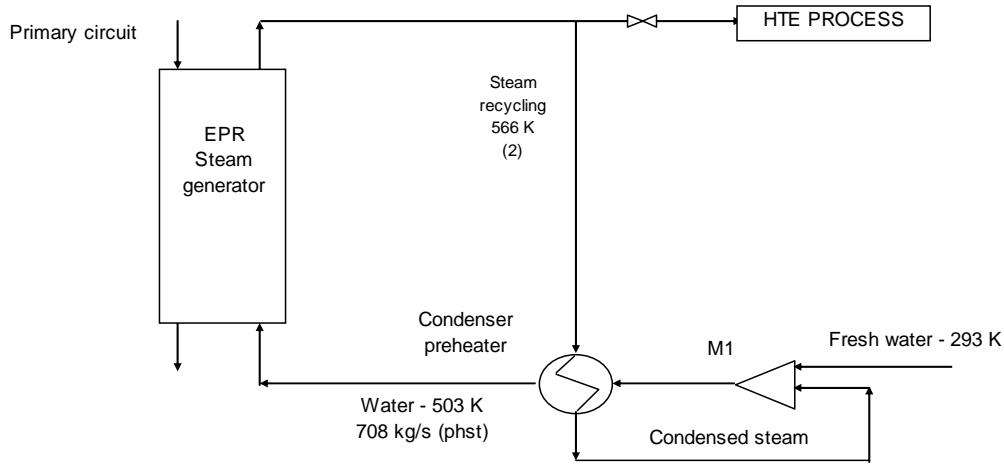


Fig 3. Schema of an EPR loop working at full steam production.

2.2 Steam production by using an SFR

For the SFR, a reactor with a tertiary water circuit is considered and we propose a steam drawing off in the turbine section. In this case, we suppose that the SFR turbine is of a steam condensation type and not a CO₂ type (figure 4) [8]. Several hypotheses have been taken into account (c.f. 2.2.2) in order to estimate the pressure and enthalpy of the turbine drawn off steam. Water steam drawn off from the turbine should be completely in gas phase and the minimal outlet temperature should be at least 473 K.

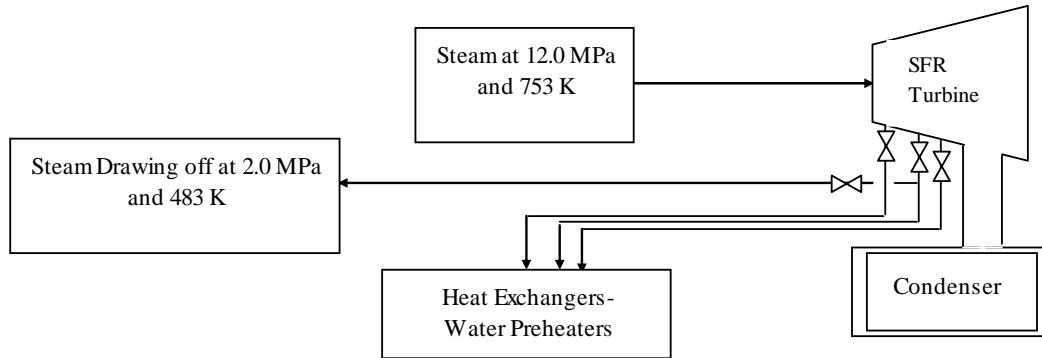


Fig 4. Schematic representation: steam drawing off from SFR turbine based on [8].

2.2.1 Operating conditions of a Sodium-cooled Fast Reactor

According to [13], the SFR low uranium consumption could lead to a lower electricity production cost; nevertheless discussions about this assumption are still in progress. For a first technical approach, a SFR of 40 MW_{th} has been studied in this work based on the schema of Srinivisan et al. [8]. This reactor presents primary and secondary cooling circuits with liquid sodium at 653 K in the inlet stream and 788 K in the outlet stream. In the third water circuit steam is produced. For this reactor, the water mass flow in the third circuit is 19.45 kg/s. The generated steam reaches 753 K and a pressure close to 12 MPa. This steam enters a condensation turbine of 16.4 MW_e. Several drawing offs in the turbine stages are currently used to preheat the liquid water in the third circuit. An average of reactor efficiencies is estimated at 44.9% [8, 14] with an annual availability close to 80%.

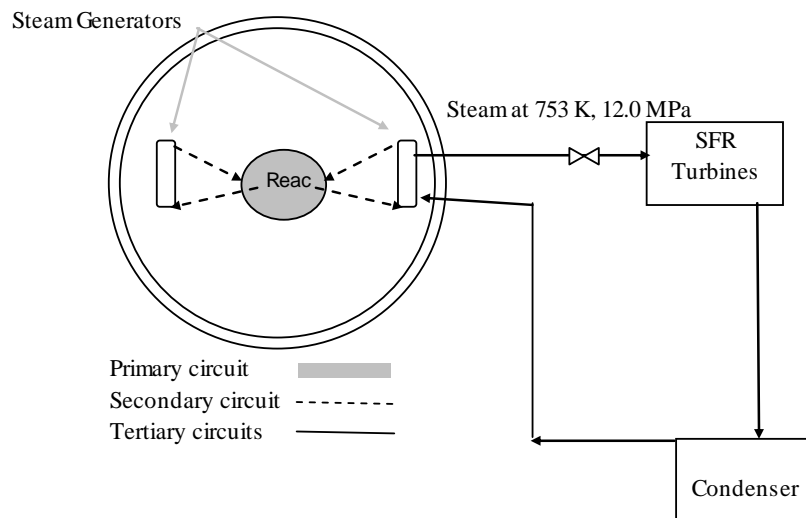


Fig 5. Schema of an SFR 40 MW_{th}, based on Srinivisan et al. [8] work.

2.2.2 Drawing off of water steam of turbine section

In order to generate water steam for the hydrogen production by HTE, we studied the SFR operation schema presented in figures 4 and 5 [8]. We propose to obtain the water steam by increasing the drawing off of reactors turbine. Steam entering the turbine presents an enthalpy of 3290 kJ/kg at 753 K and 12.0 MPa, which means that it is an overheated steam. Water boiling point at this pressure is 601 K. The enthalpy and pressure decrease as steam is expanded in the different stages of the turbine. Using equations (4) and (5), we carried out the estimation

of temperature decrease in the turbine as a function of pressure. Overheated steam enthalpy and temperature decrease until they reach the saturated vapour properties, as shown in figure 6.

$$T_2 = e^{\left(\frac{\ln \frac{P_2}{P_1}}{Cp_{vap}/R} + \ln T_1 \right)} \quad (4)$$

$$\frac{Cp_{vap}}{R} = 3.47 + 1.45 \times 10^{-3} T_{vap} + \frac{1.21 \times 10^4}{T_{vap}^2} \quad (5)$$

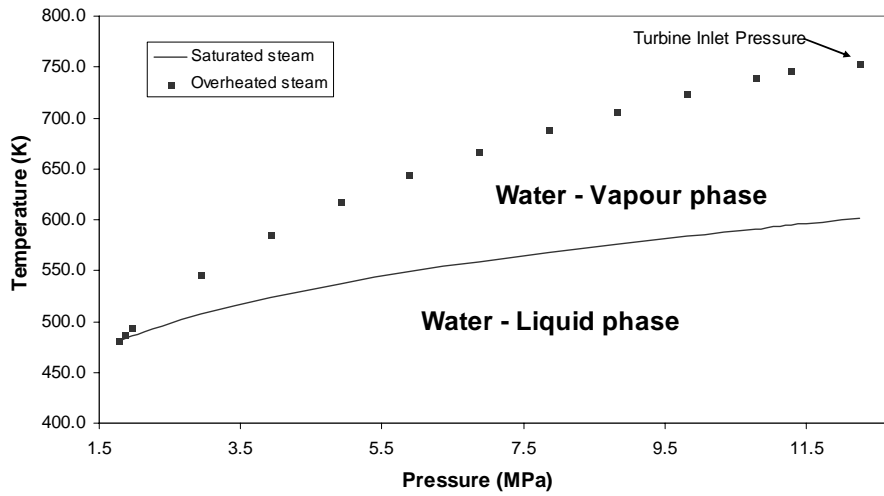


Fig 6. Pressure decrease of overheated steam in a 40 MW_{th} SFR turbine

A saturated vapour is produced when the turbines pressure is around 1.8 MPa. If steam is used for the HTE process, we propose to make the drawing off of steam at the turbine stage where steam is still overheated. A drawing off at 2 MPa could be a good choice in order to obtain steam at ~483 K and to avoid the steam condensation once we are near the dew point. Observing the energy recovery, a pressure decrease until saturation pressure, at 2.0 MPa, shows that only 504 kJ/kg from 2500 kJ/kg would be recovered from overheated steam in the turbine. Supposing that no drawing off has been made until 2.0 MPa, energy recovery in the turbine would reach 9.8 MW_{th}. A slight variation of 1% of steam flow could lead to 8.82 MW_{th} and a steam drawing off of 0.195 kg/s, which could result in a 0.022 kg/s hydrogen flow, if HTE process works at a 100% conversion.

Moreover, a 1% steam flow deviation, for hydrogen production, of a SFR as the BN-1800 [15], would allow an annual hydrogen production of 5.08 x 10⁷ kg or ~1% of the European hydrogen production. The water steam flow would be of 2.01 kg/s and the power in the electrolysis would be around 20 MW_e.

Something interesting in this kind of drawing off is that electricity and steam production at the same time allow an important quantity of hydrogen production without losing an important energy amount in the turbine, and the drawing off pressure of 2 MPa diminishes the danger of damaging the electrolyser, which is currently under discussion.

2.3 Steam production by using a VHTR

Concerning the steam produced by the VHTR, we retained the same assumptions exposed in [9], [16] and [17] that consider a nuclear reactor with a helium Brayton cycle and a turbine

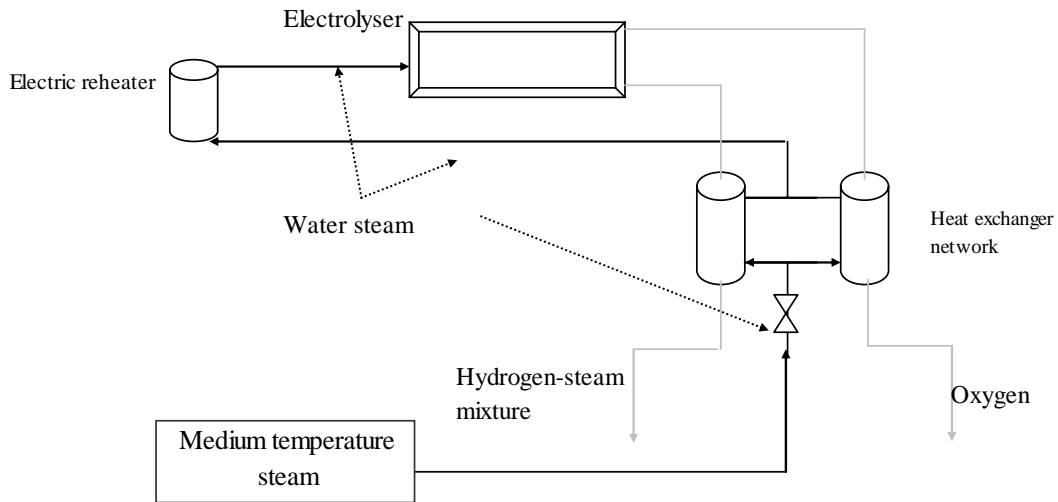


Fig 8. Schema of HTE process coupled with medium temperature water steam production.

In the present work, the water steam inlet temperature and pressure for the HTE process depend on the energy source and the pressure drop. Table 2 shows the properties of water steam in the inlet stream of HTE process for the EPR, SFR and VHTR.

Table 2. HTE process - Inlet steam stream properties depending on the nuclear reactor type: EPR, SFR and VHTR.

<i>HTE- Parameter</i>	<i>EPR</i>	<i>SFR</i>	<i>VHTR</i>
Inlet steam temperature and pressure	523 K (4 MPa) 506 K (3 MPa) 471 K (1.5 Mpa)	483 K (2 MPa)	743 K (3MPa)
Inlet steam enthalpy (kJ/kg water)	2762.8	2794.0	3400.0

4. Techno-economic evaluation: hydrogen production costs

For the electrolyser, as in Sigurvinsson et al. [18], modelling is based on Nerst equation adjusted for over-voltages, which were evaluated in analogy with solid oxide fuel cells (SOFC). Electricity used for HTE would be provided by dedicated reactors at a production cost. The cost of electrolyser retains the following hypotheses from Sigurvinsson et al. [18]:

- The investment is proportional to the surface of the electrolyser.
- The operation lifespan of the electrolyser is assumed to be constant for large ranges of temperatures, voltages and current densities. It has been estimated a target lifespan value of 5 years.
- The target objective for SOEC cost in Werkoff et al. [19] presents a 2000 €/kW unit cost for cells with a surface power density of 0.5 W/cm². We compared with Thijssen work [20], about SOFC cost, which presents that actual SOFC cost is function of manufacturing volume, which is around 1400 €/kW when a production volume of 5 MW/year is manufactured. In order to assess the long-term potentiality of the HTE, the SOEC cost of 2000 €/kW is considered in this work, even if a reduction in this cost is envisaged in the next years. Further, as in Sigurvinsson et al. [18], the electrolyser investment cost is then expressed by:

$$C_{i,elec} = P_{tot,useful} \times 2000 \times \left[\frac{0.5}{j \times U_{electrolyser}} \right] \quad (7)$$

The optimisation procedure consists in minimising an objective function which takes into account operating as well as investment costs. The heat exchanger networks and the electrolyser are optimised by minimising the production cost per kg of hydrogen, estimated by using equation (6). The optimisation was achieved using genetic algorithms.

$$CTA = \frac{\sum_{t=1}^{ti+te} [(C_{i,exch})_t + (C_{i,elec})_t + (C_{o,th})_t + (C_{o,elec})_t] (1 + \tau)^{-t}}{\sum_{t=1}^{Ti+Te} [H_t (1 + \tau)^{-t}]} \quad (6)$$

Several costs hypotheses have been taken into account in this optimisation. We first considered that the electricity cost corresponds to the electricity production cost by each nuclear reactor. So, for the EPR we considered the current cost of electricity produced, corresponding to 33 €/MWh_e [21]. Taking into account that the SFR costs are not still clarified and which are in current discussions, in this work we will assume an electricity production cost selected from [14], for Russian nuclear reactors. The sodium reactor is the BN-1800 reactor, which presents a cost of 80% of EPR electricity production cost. We will consider a value of 22.7 €/MWh_e. For the VHTR, electricity cost would be fixed at 41.0 €/MWh_e [22]. Electrolyser power units of 200 kW, which produce 40500 kg hydrogen per year, have been evaluated. For all the Nuclear-HTE couplings, the thermal energy production costs for each reactor were estimated using their design efficiency; the HTE discount rate, the availability, hydrogen production cost sensibility to electricity cost and other results are shown in Table 3.

Table 3. Model parameters and results for each nuclear reactor coupled with the HTE.

t_e	Number of years in use	30	years
t_i	Number of years of investment	3	years
Availability of the process		80	%
Discount rate		6	%
$c_{i,exch}$	cost of low temperature exchangers	400	€m ²
	cost of medium temperature exchangers	800	€m ²
	cost of high temperature exchangers	4000	€m ²
$C_{o,th}$	thermal consumption	electricity cost x efficiency	€MWh _{th}
$C_{o,elec}$	electricity cost (base)		Efficiency
	EPR	33.0 €MWh _e	36%
	SFR	22.7 €MWh _e	45%
	VHTR	40.0 €MWh _e	48%
Electrolyser power kW			200
H_t	Hydrogen annual production - kg/year		40539
Hydrogen production cost		HTE Pressure MPa	€/kg hydrogen
	EPR	4.05	2.5
		3.02	2.5
		1.52	2.4
	SFR	2.00	2.0
	VHTR	3.00	2.7
Hydrogen production cost with Electricity cost =1.5 times the initial value		HTE Pressure MPa	€/kg hydrogen
	EPR	4.05	3.0
		3.02	3.0
		1.52	2.9
	SFR	2.00	2.4
	VHTR	3.00	3.5

5. Discussion

In this kind of coupling, between a nuclear reactor and the HTE, the electricity cost is the most important variable if lower hydrogen production costs are targeted, and it has been presented in table 3. Hydrogen production cost for the EPR-HTE coupling does not vary more than 4% if the inlet steam stream pressure presents an isenthalpic variation of 3.0 MPa, which intrinsically

leads to a decrease of the inlet steam stream temperature. In the other hand, we evaluated the impact of a modification of the electricity cost from the electricity production cost to 1.5 times for each reactor, based on 33.0 €/MWh_e, 22.7€/MWh_e and 40.0 €/MWh_e for the EPR, SFR and VHTR respectively. Hydrogen production cost increased up to 25% if the electricity cost is 1.5 the electricity production cost. In figure 9, we present the hydrogen production cost compared with the actual hydrogen production cost by SMR. After the SMR, the EPR and the SFR present the best hydrogen production cost. Nevertheless, for these three couplings, the study of minimal security distance between the nuclear reactor and the HTE unit should be carried out in order to evaluate the units connection cost and its impact on hydrogen production cost.

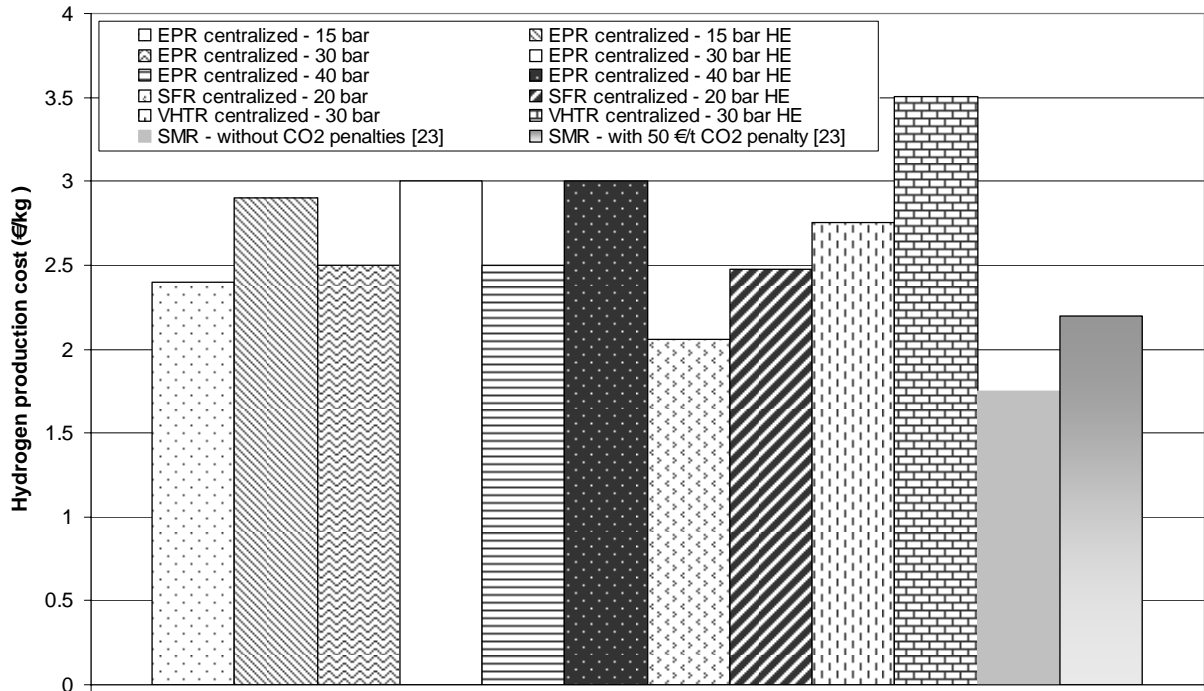


Fig 9. Hydrogen production cost for different HTE-nuclear reactor couplings: EPR, SFR, VHTR.

Being sure that no hazardous materials are passing through from the primary circuits to the steam line in the nuclear reactors encourages us to propose the drawing off or the change of usage of steam generators from nuclear reactors, usually focused on the electrical power generation. This operation procedure could agree with the idea of using nuclear reactors in a steady state and a cogeneration operation, electricity and hydrogen, which could be attractive for a plant operation point of view, because of the decrease in thermal and mechanic constraints due to exploitation changes. Moreover, nuclear reactor operation at a quasi-steady state could lead to an extra economic profit producing hydrogen during off-peak periods.

Conclusion

Hydrogen production by HTE and nuclear coupling, specifically for EPR and SFR presents a high competitive production cost due to the low electricity cost for both reactors. Let us underline once again that the investment was taken into account as target values (unit investment and life expectancy). Considering the Russian SFR electricity cost, hydrogen could be produced between 2.0 and 2.4 €/kg and 2.4 to 3.0 €/kg by using an EPR. As presented in all the results for the three nuclear reactors, the influence of the electricity cost has been found much more important than the inlet steam temperature in the HTE process. Besides, we found a

high potentiality for hydrogen production by using the EPR and SFR steam, even if 1% of their steam flow is used in the HTE process. In order to include safety considerations in the assessment of the hydrogen production cost as evaluated in the present work, future studies could take into account other constraints such as the safety distance between the nuclear reactor and the HTE process.

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