Optimized Clean Hydrogen Production using Nuclear Small Modular Reactors and Renewable Energy Sources: a Review

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1 Introduction As the world's population and economy grow while people migrate from rural areas to urban areas, the demand for energy rises [1]. Most of the modern electric energy comes globally from fossil fuels (hydrocarbons) [2], which are depleted and constrained by geographical distribution and extraction ease [3,4]. The constant use of hydrocarbon-based energy resulted in significant increases of CO_2 and Greenhouse Gases in the atmosphere and has been indicated as the primary cause of global warming [5]. Sustainable and renewable energy resources play a critical role in the world's future in order to mitigate global warming and maintain a clean environment [6–9]. Electric energy can be challenging to obtain from renewable energy sources at a very competitive price. In fact, one of the most striking features of these types of energy sources is its variability and irregularity [10]. It is then necessary to implement efficient and large-scale technical solutions to address these problems. To cope with the volatility and discontinuity of renewable energy sources, large-scale storage systems have been proposed and designed to meet the market demand [11]. By transferring generated energy on multiple time scales, storage devices are able to decouple supply and demand (hourly, daily, and seasonally) [12].

Hydrogen is a good energy transporter when it comes to storing energy [13–16]. Furthermore, Hydrogen is already a commodity that is utilized as a feedstock in a variety of industrial applications, from refineries to the manufacturing of ammonia and methanol [17]. Hydrogen-based energy storage systems are rising in importance for large-scale energy storage due to their ability to be stored and transported, as well as for cost effectiveness [3,13,18]. From less than 20 Mt in 1975 to more than 70 Mt in 2018, the global demand for pure hydrogen has surged dramatically [19]. While several researchers support the use of hydrogen as an energy carrier for the reasons just described [20], most of the latest studies, have however concluded that a fully hydrogen-dependent economy is still disputed and unattainable [13,21], despite the fact that it has just begun to show promise [22]. Whatever the difficulties, the trend is toward clean hydrogen generation to reduce CO_2 emissions and meet global energy demand [5,14,23–25].

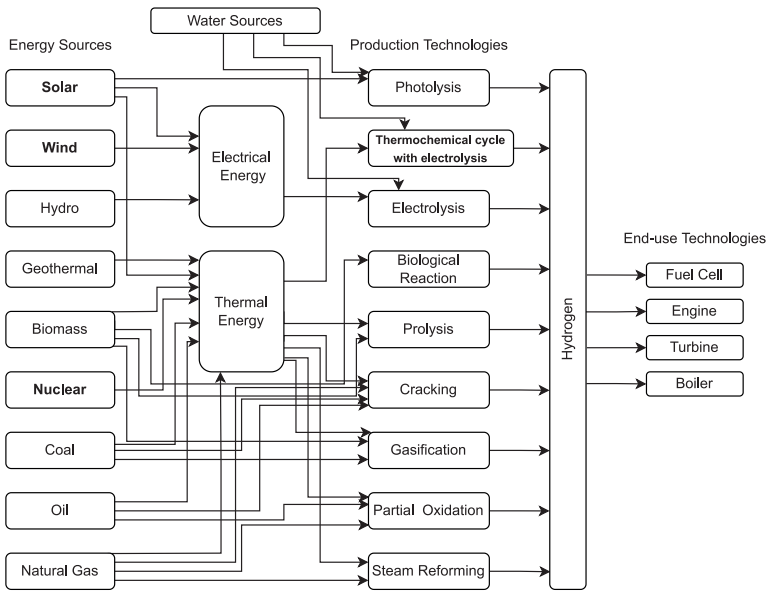

Fig. 1
The most common alternate ways for producing hydrogen from energy sources as described by [26].

According to the type of energy sources, hydrogen can be named. The use of a color-coded approach to describe hydrogen generating technology is becoming more common. Hydrogen production methods according to colors are indicated in Fig. 2. The following are the key colors that are being considered [30]:

- Grey (or brown/black) hydrogen, which is produced by fossil fuels (mostly natural gas and coal) and emits carbon dioxide;
- Blue hydrogen, which is produced by combining grey hydrogen with carbon capture and storage (CCS) to avoid the majority of the process' GHG emissions;

- Turquoise hydrogen, which is produced by pyrolysis of a fossil fuel and produces solid carbon as a by-product;
- Green hydrogen, when produced by electrolyzers powered by renewable energy (and in some situations, other bioenergy-based processes like biomethane reforming or solid biomass gasification);
- Yellow (or purple) hydrogen, when produced by electrolyzers powered by nuclear power.

Traditional water electrolysis, steam reforming, steam electrolysis at high temperatures, hybrid and thermochemical cycles are only a few of the approaches documented in the literature that can produce heat and electricity while also creating hydrogen from water in the same nuclear power reactor [26,30]. One of the most attractive technologies is the nuclear hybrid energy system (NHES). The NHES can generate hydrogen as well as low-cost power [31,32].

Due to the complexity of NHES, when optimized, NHES can be more efficient [32]. Multi-objective optimization in the NHES is a very complex aspect of optimization processes because almost all real-world optimization problems are formulated using multiple conflicting objectives. The usual way to solve such problems is to combine multiple objectives into one, but the right approach tries to solve the multi-objective optimization problem in the real world. Artificial intelligence and algorithms can be used to optimize a variety of processes in complicated systems [8,23,33–37]. Moreover, for linear, integer, and nonlinear optimization, the Lindo® What's Best (or similar) tool can be used [38,39]. The tool provides the best answer with defined constructions and parameters [38]. Thus, the purpose of this paper is to explore and report the most recent technologies proposed to generate hydrogen based on nuclear and renewable energy using optimization techniques.

Briefly, this study provides an overview of nuclear-renewable clean hydrogen generation processes, with a focus on basically water-based approaches. In addition to this, it contains an overview of small modular reactors with its temperature ranges and potential usage areas. It continues by giving information about hydrogen such as potential uses in different sectors. In the next sections, there is a comparison of hydrogen production technologies, namely, thermochemical cycles and electrolysis in terms of cost, efficiencies, global warming potential (GWP) etc. and followed by, this research indicates technology readiness level of the hydrogen production technologies. Finally, the goal of this research is to optimize each stage of the hybrid system in order to achieve better outputs while taking into account complexity and multi-objectivity.

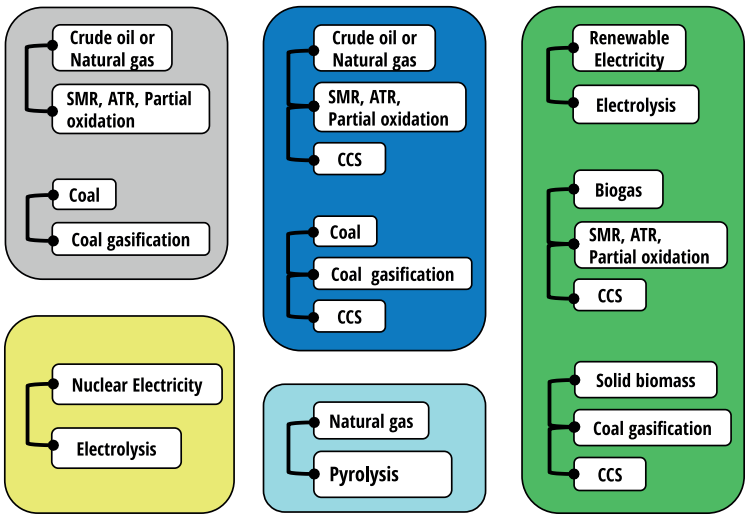

Fig. 2
Hydrogen production methods according to most commonly used color schemes.

2. Nuclear Power Plant

Nuclear power plants produce heat energy without emitting carbon dioxide due to nuclear (fission) processes. Heat is utilized to generate steam, which drives a steam turbine attached to an electricity generator, as characteristic of thermal power plants. There are approximately 440 nuclear power reactors operating globally providing approximately 11.5 % of the world's electricity demand [40,41]. Nuclear power plants have reduced CO_2 emissions by 60 gigatons during the previous 50 years [42]. Table 1 shows a summary of information of six different nuclear reactors in terms of coolant type, neutron spectrum, capacity (MWe), fuel cycle and outlet temperature (°C).

It is feasible to produce hydrogen using a nuclear reactor due to its great thermal energy capabilities [50,51]. There are numerous technologies and techniques for producing hydrogen from a variety of sources, including fossil fuels, renewable sources and nuclear energy [22,52,53]. The nuclear hybrid energy system is one of the most appealing technologies (NHES) [2]. The NHES can produce both hydrogen and low-cost electricity [31,54]. The same nuclear power reactor can deliver heat and electricity while also producing hydrogen from water with different methods [54]: water electrolysis, steam reforming, steam electrolysis at high temperatures, hybrid and thermochemical cycles are just a few of the techniques covered in the literature [6,55,56].

According to the capacity, nuclear power reactors are divided into three, which are small, medium

	Supercritical-Water-Cooled Reactor	Gas-Cooled Fast Reactor	Lead-Cooled Fast Reactor	Molten Salt-Cooled Reactor	Sodium-Cooled Fast Reactor	Very-High Temperature Reactor
Coolant	Water	Helium	Lead/Lead-Bismuth	Fluoride Salts	Sodium	Helium
Neutron Spectrum	Thermal/Fast	Fast	Fast	Thermal/Fast	Fast	Thermal
Capacity (MWe)	300-1500	1-200	20-1000	800-700	50-1600	250-300
Fuel Cycle	Open/Closed	Closed	Closed	Closed	Closed	Open
Outlet temperature (°C)	510-625	850	480-570	700-800	500-550	900-100
Reference	[43,44]	[44–46]	[44,47]	[44,47]	[44,47]	[48,49]

Tab. 1
The data of six distinct nuclear reactors.

and large reactors [57]. Currently, as small modular reactors (SMRs) are promising technology, this study continues with SMRs in the section 4.

3. Generation-IV Nuclear Reactors

Generation IV's six reactor concepts were first proposed by the US DOE and under the Generation IV International Forum (GIF): select nations proposed advancing the development of one or more of GEN IV concepts. Originally, two to three concepts were slated to be (down) selected and constructed for operation by 2030. As part of the Generation IV initiatives, the US proposed interest in the Next Generation Nuclear Plant (NGNP) as a type of VHTR with accompanying interest in a hydrogen production plant (INL) [58] and according to Patterson [46], performed studies of (State of) Hawaii to produce liquid fuel from biomass by hosting a VHTR plant. The use of CO_2 gas in the VHTR also peaked interest in supercritical phenomena (CO_2, light water) and higher overall plant efficiencies, due to potential downsizing of turbine components and the availability of printed circuit heat exchangers (PCHE). Song et al. reported on testing a PCHE in a supercritical CO_2 Brayton cycle in partnership with ANL [59]. Finally, a US Nuclear Energy University Program by Tokuhiro et al. used a high-temperature gas circulator (to simulate a VHTR) and an intelligent control system (applied neural networks) needed to extract energy from approximately 950 °C to 50 °C [60].

When looking at traditional nuclear reactors, it is well known that they are not thermally very efficient due mostly to limitations imposed on moderator temperatures. As a result, over two-thirds of thermal energy produced in conventional nuclear reactors is wasted and lost into the environment. To make nuclear reactors more efficient, the temperature difference (ΔT between highest and lowest Rankine cycle points) must be increased: for example, by increasing coolant temperature. By doing so, thermodynamic efficiency can be increased [61].

As part of Generation-IV nuclear reactors, six different types of nuclear reactors have been developed, including the Gas-Cooled Fast Reactor (GFR), Very-High-Temperature Reactor (VHTR), Lead-Cooled Fast Reactor (LFR), Molten Salt-Cooled Fast Reactor (MSFR), Supercritical-Water-Cooled Reactor (SCWR), and Sodium-Cooled Fast Reactor (SFR). Gen-IV reactors are being developed all around the world aiming for higher cycle efficiency, high temperature steam electrolysis, high temperature thermo-chemical cycling, or hybrid water separation for hydrogen production. The SCWR, for example (Canada's Gen-IV concept) has a higher net thermal efficiency of 45 % [62], and it can be configured to produce hydrogen employing Cu-Cl thermo-chemical cycle. This cycle demands higher temperatures provided by the projected SCWR design. The reason for its higher efficiency is that SCWR can function at temperatures and pressures up to 500 °C and 28 MPa, due to the supercritical thermophysical properties gains. According to Atomic Energy of Canada Limited, the SCWR concept can generate hydrogen via Cu-Cl is shown as the most promising technology based on nuclear systems [63]. In addition to improved efficiency, Generation-IV nuclear reactors have enhanced safety and reliability, sustainability, proliferation resistance, and physical protection [64].

Generation-IV nuclear reactors are important because temperature differences (ΔT) or heat

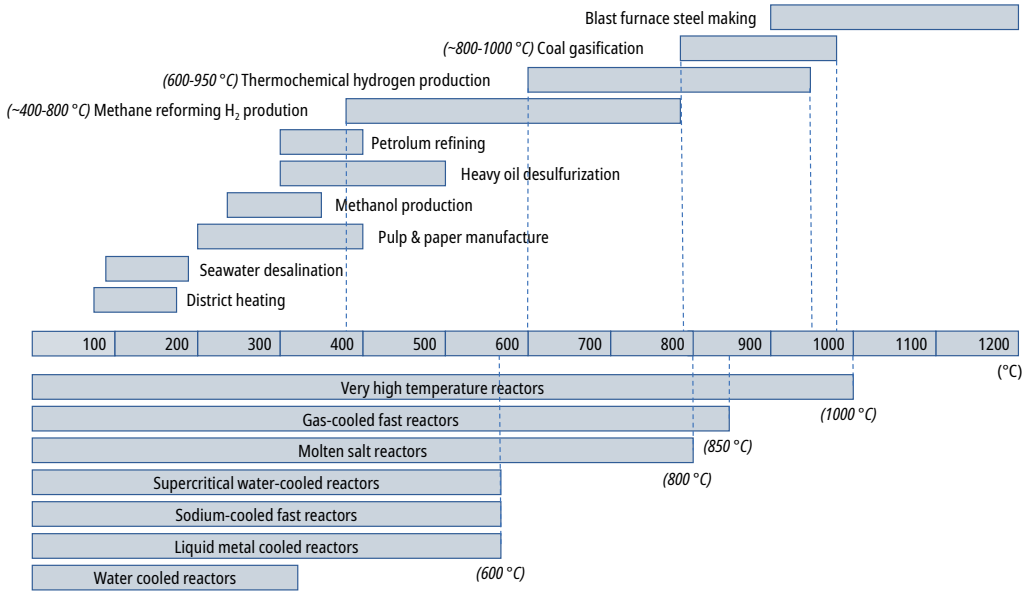

Fig. 3
SMRs for non-electric applications. Data taken from [78].

energy at high temperatures play a key role in hydrogen production [61,65]. In terms of temperature difference, concentrated solar power (CSP) technologies can be suggested for usage with Generation-IV nuclear reactors, such as SCWR, to contribute to the hydrogen economy by raising the temperature difference: CSPs in fact can meet the high-temperature requirement as reported in the literature [31,66,67].

4. Small Modular Reactors (SMRs)

SMRs are nuclear fission reactors that are a fraction of the size, power and cost of conventional large reactors. They can be built in a factory and transported to a location ready to be installed in prefabricated modules. Modular reactors thus minimize building time on-site, improve containment efficiency, reduce fabrication costs and are considered to be safer than existing conventional designs (PWR, BWR and CANDU) [68–70] . The implementation of completely passive safety elements that can operate without human involvement results in increased safety [71,72]. In comparison to conventional nuclear reactors, SMRs require less personnel [73]. SMRs are being actively designed and proposed for their capacity to overcome most of the financial and safety constraints that prevent large conventional reactors from being built globally on a large scale [74].

According to the International Atomic Energy Agency (IAEA), small reactors are those that produce an equivalent electric power of less than 300 megawatts electric (MWe) [75], while the reactors that are between 300 MWe and 700 MWe are named as “medium modular reactors” [57,76]. SMR designs cover the spectrum of possible reactors from scaled-down plants of previous designs to full Generation-IV innovative designs. Thermal-neutron reactors and fast-neutron reactors, as well as molten salt and gas-cooled reactor concepts, have all been proposed in the last years [77]. When compared to typical large nuclear power plants (NPPs of 1 GWe), Small Modular Reactors (SMRs) have significant and clear advantages. In part to these advantages, sophisticated SMRs can be used for more than just power generation. They can also be used to produce hydrogen, desalinated water, liquid transportation fuels, and some chemicals needed in the petroleum industry as depicted in Fig. 3 (when co-located) [78] .

Small Modular Reactors (SMR) with advanced features are projected to have a simpler design [79], lower cost due to their mass production, and a smaller physical footprint [80,81]. SMRs also have higher levels of safety, security, and resistance to proliferation [80–82]. Modularizing construction technique is not new in the manufacturing industry, and it has been used in the construction of major reactors in the past [83]. However, modularizations provide reduced initial capital investment, scalability, and siting flexibility in regions where traditional big reactors are not feasible nor needed [81]. Since this review focuses on nuclear-renewable hybrid systems to produce hydrogen, in the next section, renewable energy is reviewed.

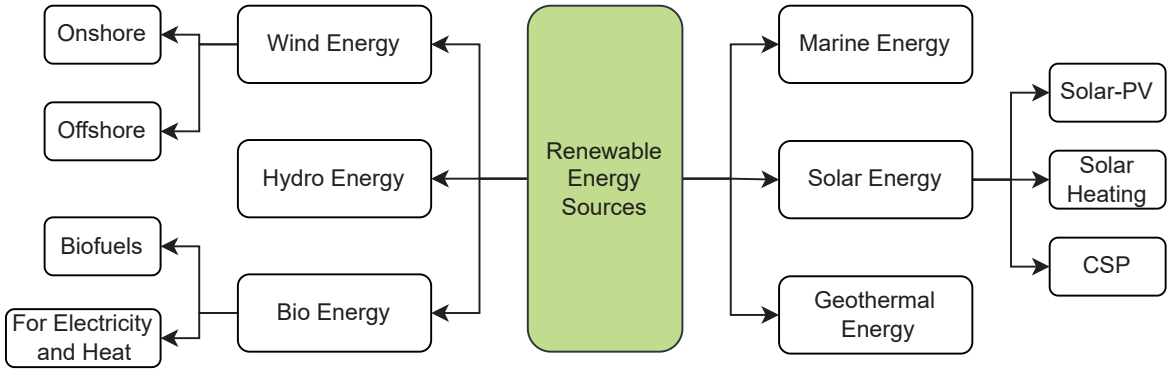

Fig. 4
An indication of renewable energy sources.

5. Renewable Energy

Traditional energy generation from fossil resources (coal, oil, and natural gas), has been very effective in providing economic development on a global scale and it plays still a key role in satisfying the world's energy needs [7,22]. However, global primary energy consumption is increasing due to increasing population and rising energy demand due to improved living standards [1]. Renewable energy contributes to the majority of the greenhouse gas emissions reductions required between now and with 2050 in mind to keep global average surface temperature rise below two degrees Celsius [7]. Thus, renewable energy sources have begun to gain significance in order to meet the rising energy demand of the world and to reduce carbon dioxide emissions in terms of environmental issues [14]. We can prevent future extreme weather and climate consequences by using renewable energy sources, which reduce greenhouse gas emissions ensuring reliable, timely, and cost-effective energy delivery [84]. Deployment is key.

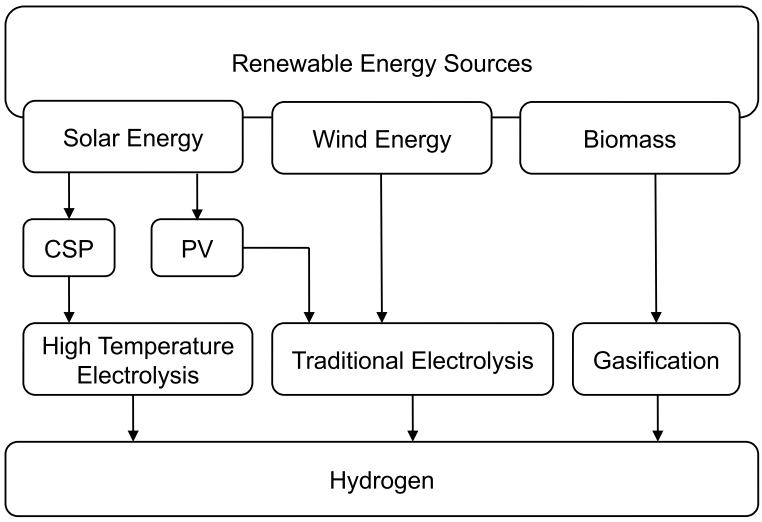

Fig. 5
Hydrogen production methods with renewable energy.

Renewable energy is derived from renewable resources that are regenerated naturally on a human timescale, such as carbon-neutral sources as sunshine, wind, rain, tides, waves, and geothermal heat [85]. Despite the fact that the majority of renewable energy sources are sustainable, others, such as biomass are not and are finite (eroding possibly other feedstocks) [6]. Fig. 4 depicts a breakdown of renewable energy sources [86]. Renewable energy sources are transformed into useful energy forms such as electricity, fuels, hydrogen, and heat thanks to renewable energy technology [87].

Finding more dependable, sustainable, and diversified energy sources might be a realistic option for reducing and eliminating greenhouse gas emissions while fulfilling global energy demands. As a consequence, hydrogen has several benefits over other choices and may be utilized to reduce pollution and dependency on imported oil [5,88,89]. Although hydrogen is not a primary energy source, it becomes an attractive energy carrier when separated from other elements utilizing an energy source [20,67,90]. Hydrogen production methods with renewable energy are shown in Fig. 5 [6,22,67]. Hydrogen is a clean energy carrier in fuel cells since it reacts with oxygen without producing CO_2 and producing water as the only by-product [90].

Some direct or indirect advantages of hydrogen can be listed as follows [22];

- Help reducing oil imports for an oil-lacking nation.
- Help achieving relative long-term sustainability compared to current energy sources.
- Change the current environment outlook by enabling emission reduction.

5.1. Solar Photovoltaic (PV)

The cost of hydrogen generated by solar electrolysis is roughly 25 times greater than fossil fuel alternatives with this technology, which is one of the

highest-cost hydrogen generation methods. The cost of solar PV, on the other hand, is projected to fall even further, as it has already dropped from 25 to 6 times [22,91]. More efforts are then needed in order for this hybrid system to be effectively competitive on the market both for cost and coupling efficiency.

5.2. Concentrated Solar Power (CSP)

It is possible to produce hydrogen by using heat energy coming from a concentrated solar power (CSP) plant [66,67]. Mirrors direct sunlight to a receiver in concentrated solar power installations. The thermal energy gathered in the receiver is utilized to power a steam turbine, which then generates electricity [92]. This CSP technology very suitable to assist nuclear power plants ensuring that heat energy at high-temperature is provided directly and without intermediate conversion for the nuclear steam superheating. Three kinds of CSP technologies meeting the high-temperature requirements, are commonly reported in the literature. These technologies are categorized according to the mirrors devices used in CSP. These are the Parabolic Trough (PT), Fresnel Reflectors (FR), Dish Receiver (DR) [31, 93]. PT technology made over 90 % in operation in 2013 [94], and recently more than 60 % of CSP systems [95]. The FR system is similar to PT collector technology, but it employs a number of ground-based, flat or slightly curved mirrors positioned at various angles to focus sunlight onto a stationary receiver several meters above the mirror region [96]. Solar power towers, also known as "central tower" power plants, "heliostat" power plants, or "power towers," are a form of solar furnace that receives concentrated sunlight through a tower. It focuses the sun's beams onto a collection tower using a system of flat, moveable mirrors known as heliostats. One possible alternative for sustainable, pollution-free energy is concentrated solar thermal power [31].

5.3. Wind Energy

This approach, which uses energy generated by wind turbines for electrolysis, has one of the most potential among renewable sources for producing pollution-free hydrogen, especially for dispersed systems [97]. The drawbacks of using wind energy to create hydrogen include not only the expensive cost of wind turbines and electrolyzers, but also the optimization of the turbine electrolyser-storage system. The cost of generating hydrogen with wind turbines is about 6-10 times as much to produce hydrogen as fossil fuel alternatives and so not yet competitive. In the future, this rate is projected to be reduced by half [22,91].

6. Hydrogen

Hydrogen is a chemical element having a H symbol and its atom number is “1”. Hydrogen (H_2) is one of the most prevalent elements in the universe, and it is found mostly in water and organic compounds on our planet [7]. It's a combustible gas that's colorless and odorless [98]. Because hydrogen's atomic weight number is 1.008 amu, it was decided that October 8th (10/08) should be designated as National Hydrogen and Fuel Cell Day in the United States [99].

Hydrogen is extensively employed in industrial areas such as petrochemicals, agriculture (such as ammonia for fertilizers), food processing, plastics, manufacturing, and, increasingly, transportation [100].

One of the most important components in the petroleum and petrochemical sectors is hydrogen. Because of novel fuel cell applications, hydrogen has recently become more important [35,101]. Hydrogen can be produced utilizing a variety of methods, including various feedstocks, routes, and technologies, as well as various energy sources such as fossil fuels and renewable energy sources [31,35,102–104].

Steam reforming of natural gas (methane) has become the most cost-effective and widely used process for hydrogen production, accounting for around half of all hydrogen produced worldwide [6,105,106]. According to [100], currently, over 97 % of the world's hydrogen is produced by steam-methane reforming of fossil fuels like coal or methane (SMR), which emits significant amounts of CO_2 into the atmosphere [107]. The global warming potential of hydrogen generation via the steam methane reforming method has been estimated to be 13.7 kg CO_2 per kilogram of net hydrogen generated (CO_2 consists of 77.6 % of the system's global warming potential) [107,108]. A typical steam methane reforming hydrogen plant that produces one million cubic meters of hydrogen per day emits 0.3-0.4 million standard cubic meters of CO_2, which is generally dumped into the atmosphere [107]. In the next section, potential nuclear based hydrogen generation methods are explained.

Hydrogen can be part of an integrated system that offers dispersed renewable energy while also being connected to a base-loaded nuclear power grid, where it can be stored and utilized to create electricity for a facility or in mobility applications [109].

6.1. Prediction of Hydrogen's Future against Gasoline

Efficiency can be substantially reduced to an economics issue to be handled at the entire value chain level provided that CO_2 emissions are taken into account. This is significant because hydrogen can be used far more efficiently in some applications and can be produced without emitting almost no greenhouse gases. A hydrogen fuel cell in a vehicle, for instance, has about 60 % efficiency, while an internal combustion gasoline engine has approximately 20 % efficiency [19]. In terms of energy per unit of mass, hydrogen has three times higher energy (120.1 MJ/kg) than gasoline and contains more energy than natural gas as well. Thus, hydrogen is seen as a very promising fuel for transportation.

After taking into account the efficiency of converting hydrogen into power, the price of gasoline paid by automobile owners is roughly 10 USD/kgH_2 for hydrogen provided in most regions by 2030. It means that the hydrogen costs delivered by 2030 will be affordable when compared to expected hydrogen price (USD 7.5-9.0 per kg-hydrogen) in 2030 [19]. For these reasons, it is possible that hydrogen will be replaced by gasoline in the future years.

7. Nuclear Hydrogen Production

Nuclear Power Plants have a significant role in meeting the increasing energy demand of the world [110]. In terms of clean hydrogen generation, renewable and nuclear energy are the only carbon-free (or low-carbon) options [111]. Electrolysis utilizing electricity from intermittent renewable or dependable nuclear sources and direct utilization of heat from nuclear energy, may enable thermochemical process using high-temperature reactors, and can increase hydrogen production plans [45].

Green hydrogen is an expensive strategy compared to fossil-based hydrogen production [112]. Green hydrogen produced from renewable energy costs between US$2.56-7.39/kg-$H_2$, which is more expensive than black, blue, and grey hydrogen, as indicated in Table 2. As an example, calculation of green hydrogen cost employing traditional electrolysis (alkaline) is pointed in Table 3 [2]. To obtain 1 kg of hydrogen, 180 MJ electricity, 26.2 MJ heat energy and 11.5 kg of water are used via low-temperature electrolysis at 60 °C and 0.1 MPa. According to the prices of heat and electrical energies per unit, the product cost of 1 kg-hydrogen is equal to $US 5.92 [2] .The cost of aqua hydrogen that does not emit CO_2 is US$ 0.23 per kg-hydrogen as reported in [112]. In Table 2, the information of the costs of producing hydrogen using various technologies is given.

Moreover, using renewable energy sources is an excellent choice for clean hydrogen production, since the cost of producing hydrogen via traditional electrolysis (low temperature electrolysis) plays such a significant role in the clean hydrogen economy. For this reason, to calculate electrolytic hydrogen cost, photovoltaic (PV) panels as a clean energy source were used in a study including all major techno-economic parameters [113];

- Electricity consumption: 57.85 kWh/kg-H_2
- Investment cost: 368 $/kWe
- Operation life of the electrolyzer: 7 years
- Project lifetime: 30 years
- Discount rate: 6 %
- Hydrogen capacity production: 250 t/year

According to the study, the cost of green hydrogen produced through electrolysis is around $7/kg-$H_2$, which is more than the cost of other types of hydrogen such as black, blue, and grey hydrogen. It is also demonstrated that electricity expenses account for more than 70 % of the cost of production hydrogen using a PV energy source.

	Methods								
	Black Hydrogen without CCUS	Grey Hydrogen without CCUS		Blue Hydrogen with CCUS		Green Hydrogen			
Energy Source	Coal	Natural Gas		Coal	Natural Gas	Renewable Electricity			
Location	Canada	Canada		Canada		Canada			Europe
Hydrogen Cost (US$/ kgH₂)	1.35	1.31	0.67-1.05	1.60-2.05	1.61-1.83	7.39	2.56-6.84	2.28-3.69	2.36-8.26
Reference	[112,115]	[112,115]	[112,116]	[112,115]		[112,117]	[112,118]	[112,116]	[112,119]
Note: Hydrogen prices in €/kg are converted into US$/kgH₂.									

Tab. 2
A summary of the costs reported in the literature for producing hydrogen using various technologies. (CCUS: carbon capture use and storage)

According to another study done [114], the cost of production hydrogen employing low temperature electrolysis, which has parameters of production capacity 1500 kg/day, capital cost $0.96, feedstock $5.06, operation and maintenance cost (O&M) $0.73, is shown as $6.75 per kg-$H_2$.

Hydrogen derived from fossil fuels produces a considerable quantity of emissions, which is not good for the environment and the issue of climate change [84]. On the other hand, hydrogen can be obtained by using energy coming from nuclear power plants almost without any carbon emission. Nuclear as clean energy source can be used to separate hydrogen from the ocean water [16]. When looked from this perspective, nuclear power plants will be critical in producing hydrogen on a large scale in the future [61]. Hydrogen generation with nuclear energy is shown in Fig. 6. In this model, heat and electrical energy are transferred from nuclear power plant to hydrogen generation plant to obtain hydrogen by separating water [120].

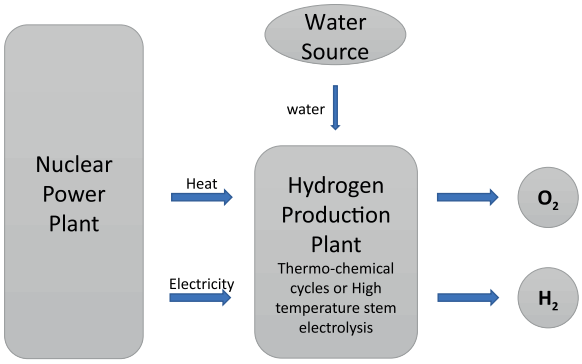

Fig. 6
A schematic of nuclear hydrogen production.

reported for generating hydrogen in such way [124]. In terms of some criteria, such as efficiency, cost analysis, complexity, industry adaptability, two thermochemical cycles have an important role in producing hydrogen: copper-chlorine and sulfur-iodine indicated as very promising in [130]. Both of them have different requirements and also different efficiency. Heat, rather than electricity, is the primary source of energy for splitting water to generate hydrogen by using sulfur-iodine (S-I) or copper-chlorine (Cu-Cl) thermo-chemical cycles [17]. In these cycles, chemicals are recovered and reused [17,124]. Sulfur-iodine thermochemical cycle requires about 850 °C which is higher than copper-chlorine's temperature requirements (around 530 °C): therefore, it can be used coupled with a Very High Temperature Nuclear Reactor (VHTR) - gas cooled [16,43,131]. Cu-Cl thermochemical cycle, on the other hand, can be preferred with other available energy sources because it requires a lower temperature than S-I [17].

Parameters		Inputs (kg H_2)		Outputs (kg H_2)	
T_{max} (°C)	60	Electricity (MJ)	180	H_2	1
Pressure (MPa)	0.1	Heat (MJ)	26.2	O_2	8
TRL	9	Water (kg)	11.5	CO_2	0
H_2 Yield eff. (HHV)**	29.8			Production cost*	$US 5.92

*Production cost (est. $US 2019).
**Assuming a power cycle conversion efficiency of 40%. (HHV: Higher heating value)

Tab. 3
Calculation of per kg of hydrogen employing alkaline electrolysis [2].

Hydrogen may be produced in a variety of ways, including steam reforming, steam reforming at high temperatures, coal gasification, conventional water electrolysis, thermo-chemical cycles, hybrid, and high temperature electrolysis, according to the literature [22,29,56,67,89,90, and 121–128].

Nuclear power plants are more effective in terms of heat generation than that of electricity. In addition to this, since thermo-chemical cycles and high temperature electrolysis require electricity and especially high temperatures which are 500-830 °C, which means requiring more heat energy than electrical energy, nuclear energy can be used to generate hydrogen [17,56,103,129].

7.1. Thermochemical Hydrogen Production Cycles

Many thermochemical hydrogen generation cycles operate on the idea of thermally separating water into oxygen and hydrogen using clean energy sources that do not emit greenhouse gases, owing to chemical compounds and reactions. In the literature, there are about 200 thermochemical cycles

7.1.1. Copper-Chlorine (Cu-Cl) Cycle

Cu-Cl cycles come in seven different varieties [44]. The four-step Cu-Cl cycle having about 43 % net efficiency [100] offers the highest energetic and exergetic efficiency, according to the researchers [132]. The heat requirements at about 530 °C for

Cu-Cl [123,133] can be met with new generation nuclear reactors or concentrated solar power (CSP) systems [134,135]. Because solar and nuclear energy are both clean sources of energy, using the Cu-CI thermochemical cycle to produce hydrogen may be preferable [133].
The four-step Cu-Cl cycle involves hydrolysis, thermolysis, electrolysis, and drying steps [122,124,136].

The first step which is hydrolysis:
$2CuCl_2(s) + H_2O(g) \rightarrow Cu_2OCl_2(s) + 2HCl(g)$
(at 375-400 °C [136]) *(1)*

The second step which is thermolysis consists in the decomposition of copper oxychloride taking place at high temperatures of about 500-530 °C;
$Cu_2OCl_2(s) \rightarrow ½\ O_2(g) + 2CuCl(l)$ *(2)*

The third step which is electrolysis;
$2CuCl(aq) + 2HCl(aq) \rightarrow H_2(g) + 2CuCl_2(aq)$
(at 25 °C) *(3)*

The fourth step (drying of aqueous cupric chloride) happens at temperature between 30 to 80 °C;
$CuCl_2(aq) \rightarrow CuCl_2(s)$ *(4)*

As the heat requirement is at a temperature below 550 °C, Super-critical water reactor (SCWR) can be used to meet the heat requirements for Cu-Cl cycle [63,89]. The Generation IV reactor (SCWR) generates electricity at a 42 percent efficiency, which translates to a net efficiency of roughly 30 percent for hydrogen production via electrolysis [100].

7.1.2. Sulfur-Iodine (S-I) Cycle

In the literature, even though there are various types of S-I cycles, the most prevalent is the three-step S-I cycle [131,137]. S-I cycle has a similar efficiency with Cu-CI [17].

The first step (exothermic) is hydrolysis:
$I_2\ (l+g) + SO_2(g) + H_2O(g) \rightarrow 2HI(g) + H_2SO_4(l)$
at 120 °C *(5)*

The second step (endothermic) is oxygen generation:
$H_2SO_4(g) \rightarrow SO_2(g) + H_2O(g) + ½O^2(g)$,
endothermic at 850 °C *(6)*

In the third step (endothermic) hydrogen production if finally obtained;
$2HI(g) \rightarrow I2(g) + H2(g)$ at 450 °C. *(7)*
This procedure needs the use of water and heat, as well as three chemical interactions. The water in this cycle is split into oxygen and hydrogen, and the other materials are recycled to be used again. Heat of at least 850 °C is necessary in the first process, known as "catalytic decomposition of sulfuric acid" [17,137]. Low pressure also contributes to safety by minimizing the risks of pressurization in chemical plants and reducing high temperature stresses. A lot of work has gone into matching this cycle to high-temperature nuclear reactors, as well as estimating total process efficiency and hydrogen cost. Early estimates suggested that the S-I processes might create hydrogen at 45 to 55 percent efficiency and co-produce hydrogen and power at a rate of above 60 percent [89].

7.2. High Temperature Electrolysis (HTE)

Electrolysis may also be used to produce hydrogen from water [20,67,100,102,103]. There are two types of electrolysis described in the literature: conventional and high temperature electrolysis [67,90]. Temperature differences are the cause of the discrepancies [90]. While typicaly electrolysis is carried out at temperatures below 100 °C [138], high temperature electrolysis needs heat at temperatures above 100 °C [56]. Due to the fact that water is in the form of steam at working temperature, high temperature electrolysis is also known as "high temperature steam electrolysis". In this section, "high temperature" refers to above 600 degrees Celsius [56].
The technique of conventional electrolysis is well-established: hydrogen is generated on the cathode by transferring energy via electrochemical cells inside the water electrolysis unit while pure oxygen is obtained on the anode [56,139]. Conventional electrolysis contributes to the production of 4 % of the world's hydrogen [140]. It means that traditional electrolysis does not meet the world's demand for hydrogen. Thus, high temperature electrolysis (HTE) is necessary for large scale hydrogen production.
High temperature electrolysis differs from regular electrolysis in that the majority of the energy required for HTE comes from heat rather than electricity. Water is decomposed into hydrogen and oxygen via thermolysis at 2500 °C; electricity then is not required [141]. Therefore, it is more efficient than traditional electrolysis because it eliminates the somewhat wasteful process of converting heat to electricity, but it requires a much higher temperature source. The HTE can use energy coming from nuclear reactors generating electricity and heat which is necessary for steam needed for electrolysis [103]. The HTE is powered by nuclear reactors, which provide electricity and heat, both of which are required to produce steam for electrolysis [89,103]. Such HTE plants might play a significant

role in grid balancing by delivering extra energy to the grid when demand is high and taking electricity from the grid when demand is low to generate hydrogen. The energy input is a mix of electricity and heat over the whole temperature range of 0 °C to 2500°C [56]. At a temperature of 850°C (a common temperature), the high temperature steam electrolysis (HTSE) requires 2.5 [kWh_e/Nm^3] and 0.92 [kWh_t/Nm^3] of electrical and thermal energy, respectively [47,56]. Because high-temperature electrolysis needs a high-temperature environment, typically more than 600 °C, nuclear reactors with Generation-IV Small Modular Reactors are ideal to ensure the heat energy needed [16,103].

An electrolysis cell in the HTE mechanism consists of a cathode (hydrogen electrode), anode (oxygen electrode) and an electrolyte. One side of the electrolyte is connected to the cathode, while the other is connected to the anode. Water is heated by external heat before entering the electrolysis cell as steam in the HTE process. As can be seen in equation (8) applying steam to the cathode of an electrolysis cell decomposes steam into hydrogen and oxygen ions. The hydrogen is then extracted as a hydrogen product, and the oxygen ion is delivered to the anode through the oxygen ion conductivity of the electrolyte. As can be observed in equation (9),

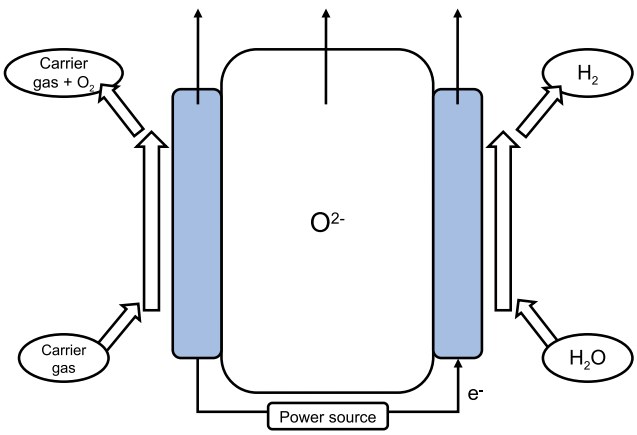

Fig. 7
A schematic of HTE mechanism.

the oxygen ion is obtained as the oxygen product at the anode. Eq. (8) and eq. (9) describe the high-temperature electrolysis processes, and eq. (10) is the sum of eq. (8) and eq. (9). Equation (10) depicts the process that splits water into hydrogen and oxygen. The HTE working mechanism is shown in Fig. 7.

$$H_2O + 2e^- \rightarrow H_2 + O^-_2 \quad (8)$$
$$O^-_2 \rightarrow ½\, O_2 + 2e^- \quad (9)$$
$$H_2O \rightarrow H_2 + ½\, O_2 \quad (10)$$

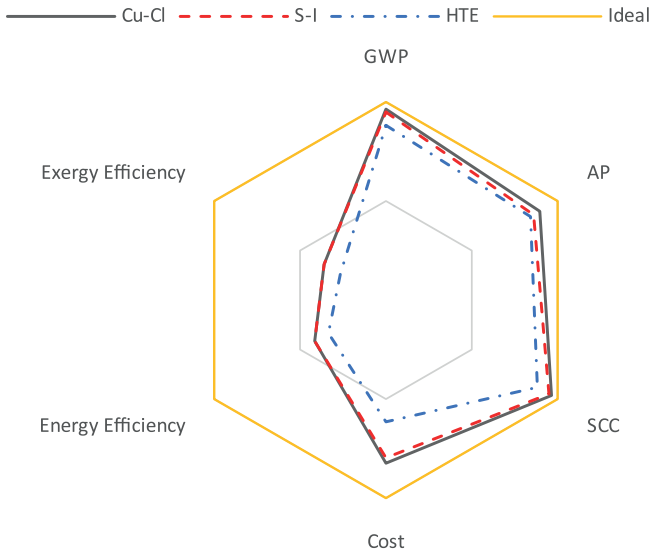

Fig. 8
Comparison of nuclear methods, namely, Cu-Cl and S-I cycles, HTE.

Despite the fact that the HTE efficiency of conversion from electricity to hydrogen may reach up to 80 %, the overall efficiency of the hybrid system (nuclear and HTE) is significantly lower due to nuclear power plant efficiencies of approximately 33 % [91].

7.3. Comparison of The Potential Methods

The performance comparison of global warming potential (GWP), acidification potential (AP), social cost of carbon (SCC), hydrogen production cost, energy and exergy efficiencies of the HTE, Cu-Cl, and S-I cycles to produce hydrogen (most common cycles used to produce hydrogen and explained in the following paragraph) using nuclear energy is shown in Fig. 8 [14,22].

7.4. Technology Readiness Level

The level of vulnerabilities for each of the proposed technologies that must be reviewed before to deployment, and this is referred to as "development risk". The technology development strategy should specify a technology development and demonstration program allowing NHES to be distributed in time. As a result, development risk has been transformed into a qualitative composite score based sub-systems readiness. The focus is on generic technology-specific components instead of industry-standard procedures like water treatment or waste management [142].

For the main components of the Nuclear-Renewable Hybrid Energy System (N-R HES) Technology Development Program Plan, each technology has defined its current Technology Readiness Level (TRL) [2,143]. In Fig. 10, the TRLs of the potential hydrogen production methods with its costs and maximum temperature requirements are depicted.

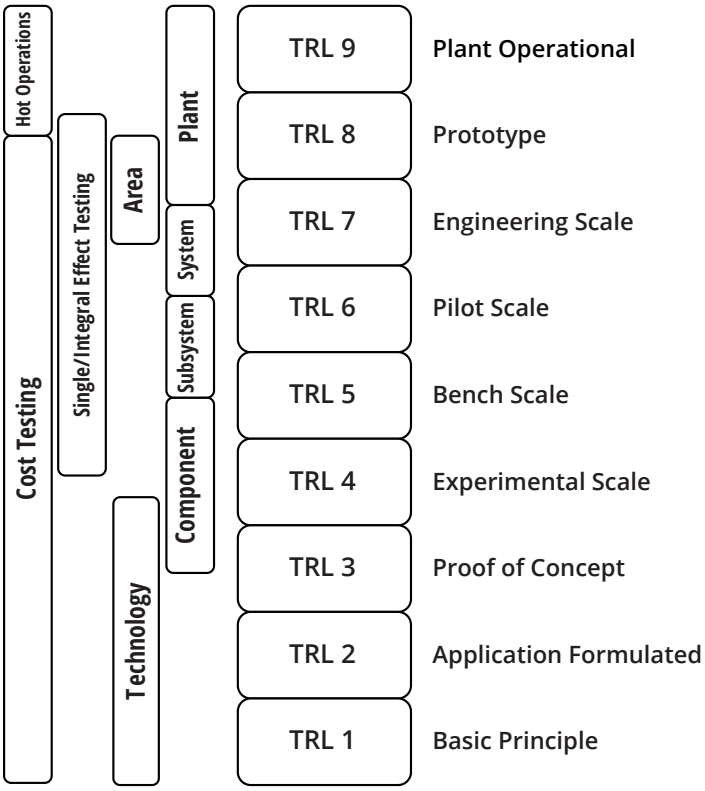

Fig. 9
An indication of TRLs [142].

When a hybrid system is evaluated in terms of TRL, the lowest component TRL score defines the system TRL score. Fig. 9 indicates a simplified overview of TRLs for N-R HES.

Three commercial electric utilities and Idaho National Laboratory have been selected to modify facilities to produce carbon-free hydrogen via electrolysis. Hydrogen will be utilized as a main energy source, as well as for transportation and storage. In the project, light water nuclear reactors are to produce 100 % carbon free hydrogen via alkaline electrolysis (low temperature electrolysis) which a TRL rating of nine. The ultimate goal of this research project is to improve the long-term economic competitiveness [144] showing the competitiveness offered by nuclear power when compared with renewable energy.

To achieve the highest efficiency outputs from the primary energy sources mentioned and the hydrogen production method compared previously, it is sensible to look at the most compatible subsystems when optimized. As a result, optimization is discussed in the following section.

8. Optimization

The term "optimization" refers to the process of obtaining the best results (outputs) possible in a particular situation [8,32,36,37,145]. An optimization problem, in its most basic form, involves selecting input values from a set of acceptable options and computing the value of a real function to maximize or minimize it. The generalization of optimization theory and techniques to new formulations is an important field of practical mathematics. Optimization, in general, entails determining the "best available" values of some objective function given a certain input, and it can apply to a wide range of objective functions and domains [145].

8.1. Complexity and Multi-objective Optimization

Engineering systems including design and analysis can have complexity, meaning multi-tasks with multiple parameters. In simple terms, complexity can be characterized by the number of variables, parameters, and multiple objectives in dynamic system behavior. For instance, while it is desirable to decrease cost, the amount of yield (hydrogen) depending on more than one parameter, is expected to increase. This exemplifies the difference between single and multiple objective optimizations.

In the literature, it can be seen that different optimization methods are applied for various areas [104,110,119,125,146–148]. One of them is Pareto Optimality (Pareto Efficiency) describing a scenario in which no choice criterion may be better off without causing at least one other preference criterion to be worse off or lose its optimal ”value” [149,150]. Pareto optimality that can be applied from economy to nuclear systems plays a role in multi-objective optimization problems having complexity [134] where trade-off choices become critical in teaching the “most suitable” system for the underlying conditions and not necessarily the “best” in mathematical terms. Thanks to flexibility of the complexity, objective functions can be redefined according to the output needed at the moment. To give a clear example, in a hybrid nuclear-renewable hydrogen production plants, when the price or demand of electricity decreases, more hydrogen can be produced instead of generating electricity. By doing so, more efficiency can be obtained.

In the nuclear technology industry, data-driven approaches have been used to improve the outputs [34]. There are a number of processes that can be optimized in complex systems by using artificial intelligence with algorithms [32,110,125,151]. The Lindo® What’s Best tool can be used for example linear, integer and nonlinear optimization [38,39]. Firstly, it was initially published for Lotus thereafter then for Microsoft Excel [152–154]. The tool gives the optimal solution with defined configurations and parameters [37].

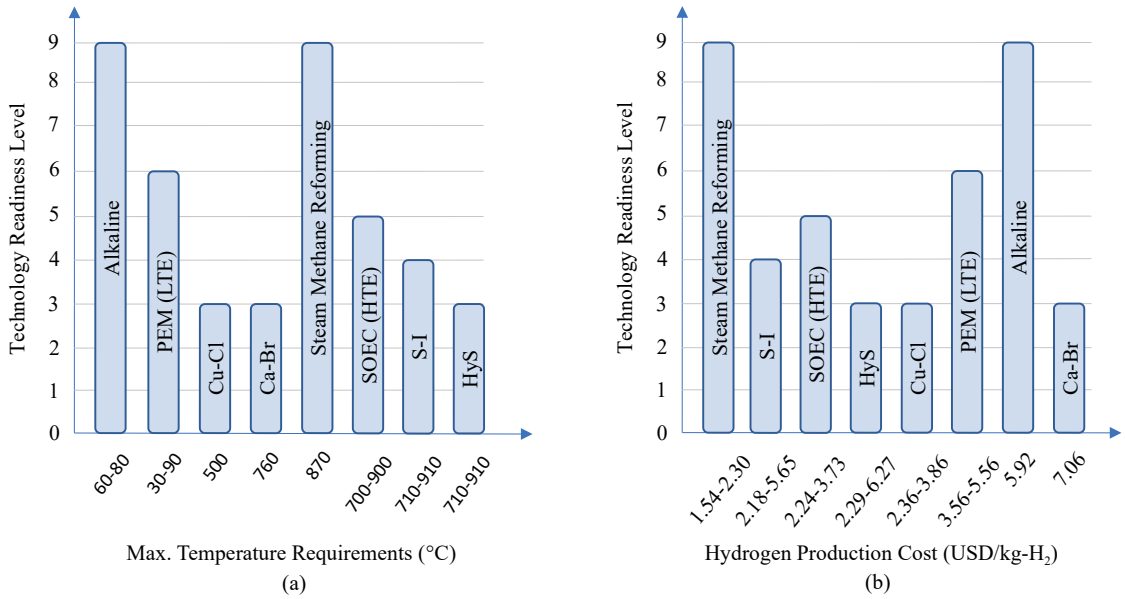

Fig. 10
TRL of different NHES hydrogen production technologies according to maximum temperature requirements (a) and hydrogen production cost (b) [2].

9. Conclusion

Hydrogen has now been widely used in a variety of industries, including fertilizer production and oil refineries. In the near future, this is likely to develop significantly to serve new sectors and larger markets in energy storage, particularly transportation, and power generation. Clean hydrogen generation via a number of thermochemical cycles and high-temperature electrolysis techniques has been shown to have a promising future. When comparing water-based hydrogen generation technologies, it is clear that HTE is not cost competitive with Cu-Cl and S-I thermochemical cycles in terms of hydrogen cost, as HTE's electricity need reduces HTE's benefits. Even though the maximum temperature requirements of the S-I cycle are higher than those of the Cu-Cl cycle, their overall efficiency and cost are remarkably similar. As a result, the Cu-Cl cycle has an advantage in terms of temperature needs. The readiness level of the S-I cycle (TRL-4), on the other hand, is higher than that of the Cu-Cl cycle (TRL-3). Furthermore, provided that Cu-Cl or S-I cycles are used to produce hydrogen with a nuclear reactor, there may be a waste of heat energy. In Fig. 3, it is seen that the waste of heat energy can be used in some industries, such as petroleum refining, heavy oil desulfurization or seawater desalination, or even data storage.

Hydrogen is a developing energy carrier that can help to significantly decarbonize the global energy and industrial sectors. As a result, creating hydrogen from renewable energy sources, as well as nuclear energy, is one of today's most important engineering challenges. In the long-term one of the key issues for reducing greenhouse gas emissions and transitioning to a low-carbon future will be represented by the innovation in the hybridization of nuclear and renewable industries as they play a crucial role for thermal and electrical energy demand. Nuclear and renewable technologies will be critical for the production of clean energy needed for complete electrification in a variety of areas, including automobiles, public transportation, construction-related vehicles, home heating, and various thermal processes in the fight against climate change. As a result, nuclear and renewable energy as primary energy sources for large-scale hydrogen generation are required to accomplish a full sustainable energy future.

In the case of nuclear energy, commercial SMR technologies, which offer compact designs, better safety, increased reliability, and lower capital investment, are advantageous and appealing for a variety of industry sectors. In comparison to traditional design, SMRs offer technological advantages ranging from safer and passively actioned system design to more robust capabilities with respect to design basis accidents, ultimately resulting in lower core damage frequency. Because each of the energy sources (renewable and nuclear) has advantages and disadvantages, hybrid energy systems are considered more successful. Because NHES are multi-objective and complex systems, improving them to create power and hydrogen can provide better outcomes. More comprehensive optimizations need to be carried out in the future, as well as the development of generic optimization methods specifically designed for the NHES. Particularly important is the implementation of specific

optimization algorithms for predicting accurately prices for hydrogen generation.

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