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Investigation of an integrated hydrogen production system based on nuclear and renewable energy sources: a new approach for sustainable hydrogen production via copper–chlorine thermochemical cycles

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SUMMARY

Hydrogen production via thermochemical water decomposition is a potential process for direct utilization of nuclear thermal energy to increase efficiency and thereby facilitate energy savings. Thermochemical water splitting with a copper–chlorine (Cu–Cl) cycle could be linked with nuclear and renewable energy sources to decompose water into its constituents, oxygen and hydrogen, through intermediate Cu and Cl compounds. In this study, we analyze a coupling of nuclear and renewable energy sources for hydrogen production by the Cu–Cl thermochemical cycle. Nuclear and renewable energy sources are reviewed to determine the most appropriate option for the Cu–Cl cycle. An environmental impact assessment is conducted and compared with conventional methods using fossil fuels and other options. The CO_2 emissions for hydrogen production are negligibly small from renewables, 38 kg/kg H_2 from coal, 27 kg/kg H_2 from oil, and 18 kg/kg H_2 from natural gas. Cost assessment studies of hydrogen production are presented for this integrated system and suggest that the cost of hydrogen production will decrease to \$2.8/kg. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS

hydrogen production; thermochemical water decomposition; nuclear; renewable energy; economic analysis; environmental impact; copper–chlorine cycle

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1. INTRODUCTION

As a result of increasing global energy consumption because of increasing population and rising living standards, the world faces challenges involving diminishing energy resources and the impairing impact of present energy consumption patterns on the global climate and consequently on humanity and on the environment. The concerns regarding global climate change are significant and require extensive research and development on alternative and clean energy sources and their applications [1–8]. The two major energy challenges globally are replacing crude oil and other fossil fuels and reducing greenhouse gas emissions.

There are various alternative energy options to fossil fuels, including solar, geothermal, hydropower, wind, and nuclear energy. Although many of the available renewable energy resources are limited because of their reliability, quality, quantity, and density, nuclear energy has the potential to contribute a significant share of energy supply without contributing to climate change. In the past, nuclear energy has been used almost exclusively for electric power generation, but the direct utilization of nuclear thermal energy for other purposes has the potential to increase efficiency and thereby facilitate energy savings. Hydrogen production via thermochemical water decomposition is a potential process for direct utilization of nuclear thermal energy. Nuclear hydrogen and power systems can complement renewable energy sources by enabling them to meet to a large extent of global energy demand through providing energy when the wind does not blow, the sun does not shine, and geothermal and hydropower energies are not available.

Thermochemical water splitting with a copper–chlorine (Cu–Cl) cycle could be linked with nuclear and renewable energy sources to decompose water into its constituents, oxygen and hydrogen, through intermediate Cu and Cl compounds. The cycle consists of five reaction main steps. Heat is transferred between various endothermic and exothermic reactions and other steps in the Cu–Cl cycle, through heat exchangers that supply or recover heat from individual processes.

In this study, we analyze a coupling of nuclear and renewable energy sources for hydrogen production through a Cu–Cl thermochemical cycle and assess the corresponding economics and environmental impacts. Nuclear and renewable energy sources are reviewed to determine the most appropriate option for the Cu–Cl cycle.

2. THE COPPER–CHLORINE CYCLE

A conceptual layout of the Cu–Cl process is illustrated in Figure 1. Thermochemical water decomposition, potentially driven by nuclear heat (or/and renewable sources), occurs via intermediate Cu and Cl compounds [9–22]. This cycle consists of three thermal reactions and one electrochemical reaction. The cycle involves five steps: (i) HCl (g) production using such equipment as a fluidized bed; (ii) oxygen production; (iii) Cu production; (iv) drying; and (v) hydrogen production. A chemical reaction takes place in each step, except drying. The chemical reactions form a closed internal loop that recycles the Cu–Cl compounds on a continuous basis, without emitting any greenhouse gases to the atmosphere.

3. INTEGRATION OF NUCLEAR AND RENEWABLE ENERGY SOURCES FOR A COPPER–CHLORINE CYCLE

Nuclear power and renewable energy are the main options to reduce the carbon intensity of commercial energy supply. Many researchers propose nuclear and renewable energy as a suitable couple to address the climate change challenge. In the transition to an almost complete renewable electricity sector consisting of a large degree of decentralized intermittent sources, flexible technologies running on command are needed. For a long time to come, nuclear energy will serve as support, makeup, and backup power (Figure 2).

In such a scheme, power generation must be from the flexible sources because demand is irregular on daily and seasonal bases. In many markets, the price of peak electricity is three to four times that of base load electricity. In the medium term, most support will come from renewable energies. The renewable plants will almost equal the peak capacity of the systems and consist mainly of flexible technologies that can ramp up and down easily. Renewable sources have a fluctuating nature. Nuclear-renewable hydrogen systems are potential solutions to the challenge of producing peak energy and also are enabling technologies for the large-scale use of renewable energy production options, such as solar and wind, in a nuclear-renewable energy system. Without hydrogen, the contributions of renewable energy will be limited because effective (cost and efficiency wise) large-scale electricity storage is not yet available. A more futuristic approach would be the serial construction of nuclear power plants running permanently at full load and directing surplus capacity (what the grid cannot absorb) to hydrogen generation. The direct production of hydrogen by water electrolysis is unlikely to become commercial because of high infrastructure costs and low efficiencies. Obtaining hydrogen by thermochemical conversion requires high-temperature reactors not commercially deployed so far. These considerations suggest that a low-temperature thermochemical cycle, such as the Cu–Cl cycle, can be an important hydrogen production option for coupling with renewable and nuclear energy sources.

Figure 2 shows a coupling of renewables with a nuclear reactor to produce hydrogen with the Cu–Cl cycle. One way to deliver a constant or any required load profile to the grid is to equip the nuclear and renewable power plants with an energy storage device, such as a regenerative fuel cell (a combination of a Cu–Cl cycle and a fuel cell with

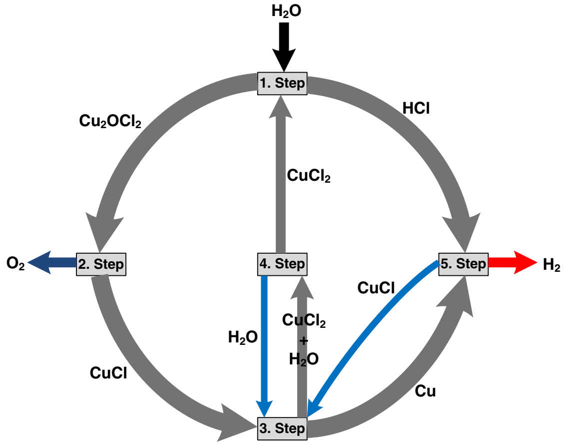

Figure 1. The copper–chlorine (Cu–Cl) hydrogen production cycle.

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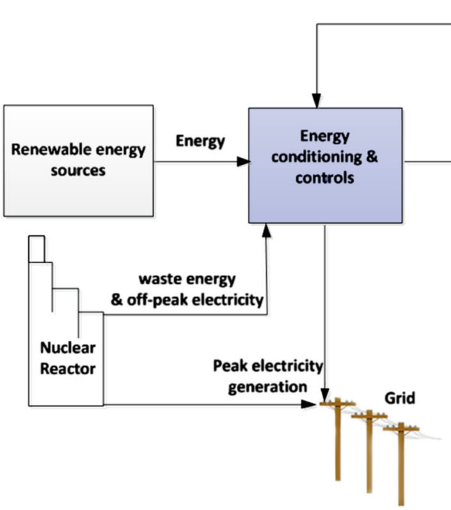

Figure 2. Coupling nuclear and renewable energy sources for a Cu–Cl cycle.

hydrogen storage), as shown in Figure 2. The power synchronization (conditioning) and control unit has an extremely complex function in this configuration. It must direct power from the renewable and nuclear power plants to either the grid or the Cu–Cl cycle and switch to fuel cell power when there is not enough power from the nuclear power plant. The renewable fuel cell system is typically less costly than a battery bank for high-power/long-duration storage. One option is to use nuclear/renewable-generated hydrogen as a fuel for home cooking and heating and/or for a fuel cell or hydrogen combustion engine-powered vehicle. Thus, production and transportation of hydrogen may be an attractive option for remote areas where the grid is not available.

4. ANALYSIS

The cost of hydrogen production consists of the following: (i) energy cost; (ii) raw material cost; and (iii) capital cost (including operational and maintenance cost). The only input raw material is water, and assuming it is free, the cost of produced hydrogen can be formulated as follows:

$$\dot{C}_{H_2} = \dot{C}_{energy} + \dot{Z} \tag{1}$$

where $\dot{C}$ denotes the cost rate of the respective stream, and $\dot{Z}$ is the cost rate associated with owning and operating the cycle. The cost rates are expressed in units of monetary cost per unit time ($/hour) or on a normalized basis ($/kg H_2). Equation (1) states that the total cost of the exiting streams (hydrogen) equals the total expenditure to obtain them: the cost of the entering streams plus capital and other costs. Because the entering streams to the Cu–Cl cycle are heat and electricity, Equation (1) can be written as follows:

$$\dot{C}_{H_2} = \dot{C}_{Heat} + \dot{C}_{Electricity} + \dot{Z} \tag{2}$$

Note that, in these cost calculations, the cost of oxygen is not included for simplicity. However, oxygen is a by-product, which can be sold or used in the energy generation process. To account for the value of oxygen, the price

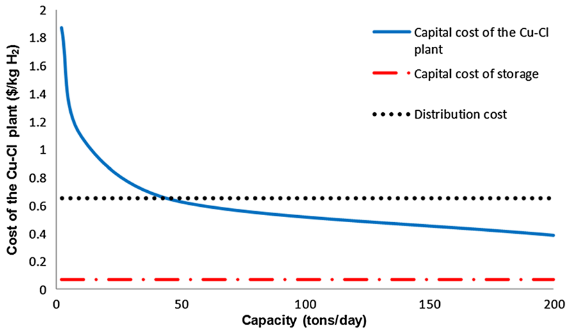

Figure 3. Costs related to the Cu–Cl cycle versus production capacity.

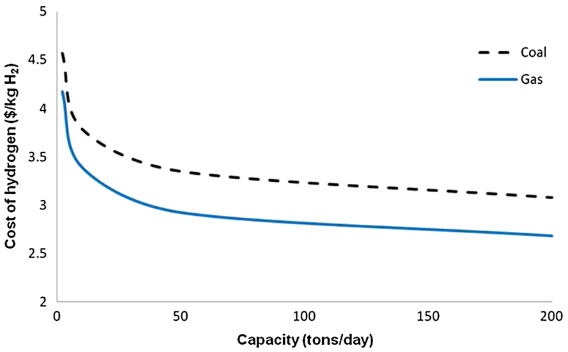

Figure 4. Cost of hydrogen production with the Cu–Cl cycle using fossil fuel energy sources.

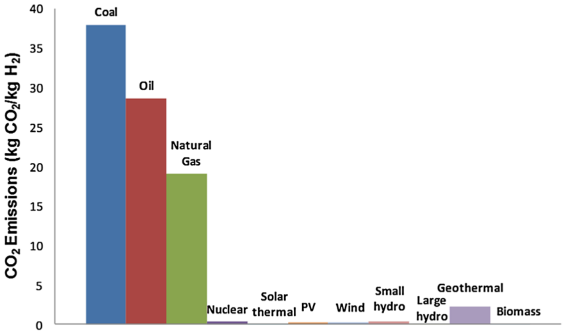

Figure 5. Carbon dioxide emissions during hydrogen production from different energy sources.

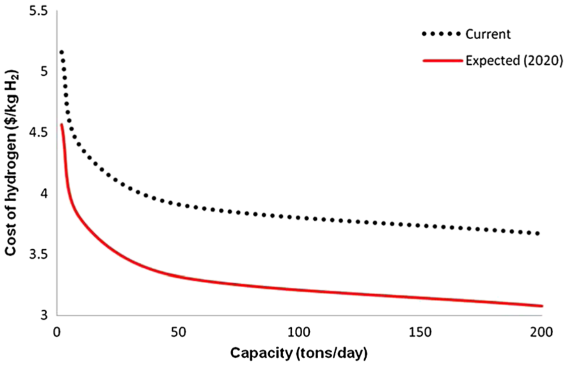

Figure 6. Cost of current and expected (2020) hydrogen production with the Cu–Cl cycle using nuclear energy sources.

of produced oxygen should be reduced from the cost of produced hydrogen.

In the cost analysis for producing hydrogen from renewable and nuclear energies, the cost of energy sources given in Ref. [13] is used. Other cost analyses of the Cu–Cl cycle by the authors have been reported elsewhere [14,15]. Note that the currency for all the costs are US dollars, escalated to May 2010 values.

5. RESULTS AND DISCUSSION

The costs associated with the Cu–Cl cycle are given in Figure 3. The main cost parameters are the capital cost of the Cu–Cl plant and cost of storage and distribution of hydrogen. The capital cost of the cycle is very high for small scale production and inversely proportional to plant capacity. Thus, before building any plant, detailed

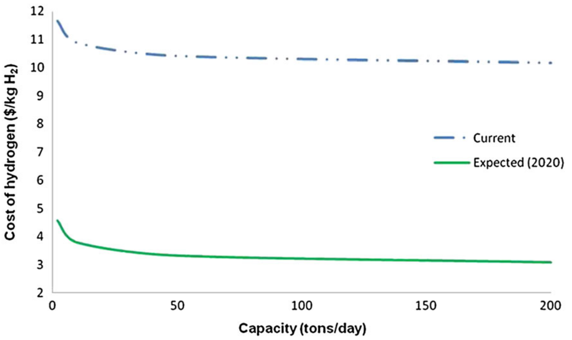

Figure 7. Cost of current and expected (2020) hydrogen production with the Cu–Cl cycle using solar energy sources.

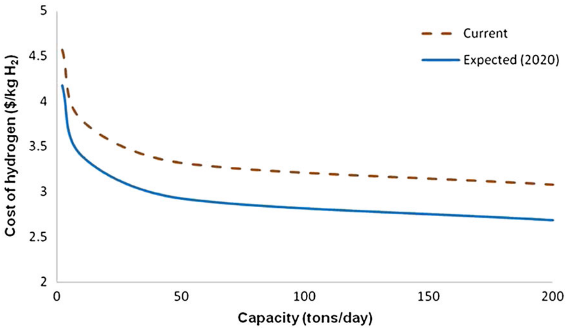

Figure 8. Cost of current and expected (2020) hydrogen production with the Cu–Cl cycle using geothermal energy sources.

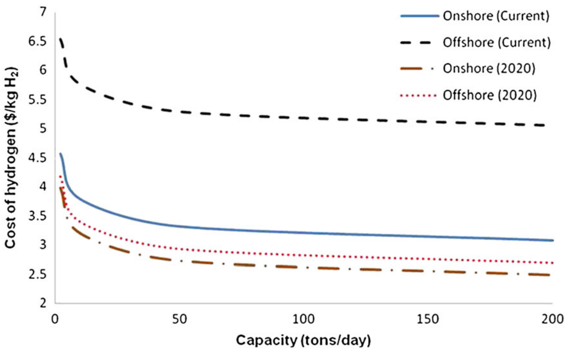

Figure 9. Cost of current and expected (2020) hydrogen production with the Cu–Cl cycle using wind energy.

economic analyses should be performed, and costs should be optimized based on capacity. For small scale production (less than 50 tons H_2/day), the capital cost of the cycle accounts for the majority of the overall cost and exceeds storage and distribution costs. For large scale production (>50 tons/day), distribution is the major cost. Distribution and storage costs are approximately constant with normalized capacity, at about \$0.7 and \$0.1/kg H_2, respectively. Note that the cost of energy needed to operate the cycle and produce hydrogen is not included here; details regarding this energy are given in the subsequent discussion, based on the energy source.

Figure 4 illustrates the cost of fossil-fuelled hydrogen production. The cost of hydrogen using natural gas is less than that for coal, and both decrease for larger capacities. These two fossil fuels seem to be the most inexpensive energy sources for hydrogen production (relative to renewable energy sources) while contributing to greenhouse gas emissions and climate change. This effect has been shown in Figure 5. In this figure, normalized CO_2 emissions during hydrogen production from different energy sources are illustrated. Note that CO_2 emission values for energy sources are taken from Ref. [13]. Using coal energy to produce hydrogen is seen to account for 38 kg of CO_2 per kg of produced hydrogen. The corresponding normalized CO_2 emissions are about 27 kg CO_2/kg H_2 for oil, 18 kg CO_2/kg H_2 for natural gas, and negligibly small (compared with fossil fuels) for renewable and nuclear sources.

Figure 6 shows the price of hydrogen produced by nuclear energy. In the figure, the cost trends are given for both current and expected future (2020) scenarios. The production cost varies between \$5.2 and \$3.7/kg H_2, whereas capacity changes from 0 to 200 tons/day, and this price range is expected to drop in the future (to about \$4.5–3.1/kg H_2 in 2020). The hydrogen price is lower for larger production capacities.

Many have highest expectations for solar energy for the future compared with other renewable sources. Currently, it is the most expensive energy source for hydrogen production (resulting in a cost of \$11–12/kg H_2), but it is expected to become much less expensive in the future (yielding a cost of \$5–3/kg H_2 by 2020) as new and cheaper solar technology become available. These results are illustrated in Figure 7, where the gap between the two curves (current and expected trends) highlights the high expectations for future solar technologies. Again, the costs are inversely proportional to Cu–Cl plant capacity.

The cost of geothermal hydrogen production using a Cu–Cl thermochemical cycle is illustrated in Figure 8, where both current and expected future hydrogen prices are given. As can be seen in the figure, the cost of geothermal energy is not expected to drop much in the future. The expectations for this technology are low (regarding the energy cost) compared with solar energy. The current cost of geothermal hydrogen production varies from \$4.5 to about 3.2/kg H_2 and decreases with increasing capacity. This range expected to drop to \$4–2.8/kg H_2 in 2020.

Figure 9 shows onshore and offshore costs of hydrogen production using wind turbines. The trends are given for both current and future expected prices. Wind energy has the second highest expectations, regarding cost, after solar. A large cost difference is observed between onshore and offshore current productions. Current hydrogen production costs varies between about \$6.5 and \$5.5/kg H_2 for offshore wind and between \$4.5 and \$3.5/kg H_2 for onshore wind. These ranges are expected to drop to \$4.0–\$2.5/kg H_2 in 2020. All costs decrease with increasing plant capacity.

6. CONCLUSIONS

Options have been assessed for integrating renewable energies, for example, solar, wind, and geothermal, with nuclear as a backup/supplementary option and to produce hydrogen as an energy carrier. Specifically, the paper presents and compares cost analyses of the Cu–Cl plant using different power sources (nuclear and renewables) for hydrogen production. An environmental impact assessment of various renewable and nuclear energy sources has been conducted and compared with conventional options with fossil fuels. The main conclusions that can be drawn from this study are as follows:

- The capital cost of the Cu–Cl cycle is very high for small scale hydrogen production and inversely proportional to plant capacity. There is a need for a further study on cost optimization.
- Distribution and storage costs appear to be constant with plant capacity, at about \$0.7 and \$0.1/kg H_2, respectively.
- Fossil fuels are the most inexpensive energy sources for hydrogen production at present (relative to renewable energy sources) but contribute to greenhouse gas emissions and consequently climate change.
- The CO_2 emissions for hydrogen production from renewables are negligibly small, whereas they are 38 kg/kg H_2 for coal, 27 kg/kg H_2 for oil, and 18 kg/kg H_2 for natural gas.
- The production cost of hydrogen, using nuclear process/waste heat, varies between \$5.2 and \$3.7/kg H_2 as the capacity varies from 0 to 200 tons/day, and these costs are expected to decrease in the future (e.g., to about \$4.5–\$3.1/kg H_2 in 2020).
- Renewable energy sources offer a great opportunity for future for sustainable and cost-effective hydrogen production.

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