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Life cycle assessment of nuclear-based hydrogen and ammonia production options: A comparative evaluation

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ABSTRACT

In this study, nuclear energy based hydrogen and ammonia production options ranging from thermochemical cycles to high-temperature electrolysis are comparatively evaluated by means of the life cycle assessment (LCA) tool. Ammonia is produced by extracting nitrogen from air and hydrogen from water and reacting them through nuclear energy. Since production of ammonia contributes about 1% of global greenhouse gas (GHG) emissions, new methods with reduced environmental impacts are under close investigation. The selected ammonia production systems are (i) three step nuclear Cu–Cl thermochemical cycle, (ii) four step nuclear Cu–Cl thermochemical cycle, (iii) five step nuclear Cu–Cl thermochemical cycle, (iv) nuclear energy based electrolysis, and (v) nuclear high temperature electrolysis. The electrolysis units for hydrogen production and a Haber–Bosch process for ammonia synthesis are utilized for the electrolysis-based options while hydrogen is produced thermochemically by means of the process heat available from the nuclear power plants for thermochemical based hydrogen production systems. The LCA results for the selected ammonia production methods show that the nuclear electrolysis based ammonia production method yields lower global warming and climate change impacts while the thermochemical based options yield higher abiotic depletion and acidification values.

Introduction

Using various types of alternative fuels in numerous applications has recently been an emerging topic. In this respect, clean and environmental-friendly fuels, such as hydrogen and ammonia, have attracted increasing attention over the conventional fossil fuels. Ammonia is potentially treated as a significant hydrogen carrier with a much higher hydrogen content. In recent years, expectations are rising for hydrogen and hydrogen carriers as a medium for storage and transportation of energy and use of renewable energy. Transportation and storage issues of hydrogen are important as hydrogen is in gas form at ambient temperature and pressure. Ammonia is produced as one of the major industrial chemicals in the world. Ammonia synthesis consumes almost 1.2% of total primary energy and contributes about 1% of global GHGs emissions [1]. Approximately 1.5 tonnes of CO_2 is

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released to the environment during the production of 1 tonne of ammonia with the current technology. Ammonia combustion characteristics have been studied for gas engines [2] which shows the practicality of ammonia usage for power production. Natural gas is considered the primary feedstock used for producing ammonia worldwide via steam methane reforming. The delivery and storage infrastructure of ammonia is similar to liquefied petroleum gas (LPG) process. Under medium pressures, both of the substances are in liquid form which brings significant benefit because of storage options. Today, vehicles running with propane are mostly accepted and used by the public since their on-board storage is possible and it is a good example for ammonia fueled vehicle opportunities since the storage and risk characteristics of both substances are similar to each other.

The usage of ammonia has been studied in the literature for vehicular applications. Zamfirescu and Dincer [3] examined the use of ammonia as a clean fuel in evaluation with further conventional fuels. They defined the possible technical benefits of ammonia usage as a sustainable fuel aimed at power production on vehicles based on some efficiency indicators containing the system efficiency, the driving distance, fuel tank compactness and the price of driving. The life cycle assessment studies of different hydrogen production methods have also been undertaken by some researchers. Ozbilen et al. [4] performed a comparative LCA study for nuclear based thermochemical hydrogen production cycles. They completed various scenarios where the source of electricity changes. Considering grid electricity for the processes, the nuclear cycles have high environmental impacts. However, when the nuclear power plant electricity and nuclear waste heat is utilized for hydrogen production, the overall environmental impact is the lowest among all scenarios. Verma and Kumar [5] offered a model to evaluate life cycle GHG emissions in hydrogen production from underground coal gasification with and without carbon capturing. Utilization of carbon capturing technology permits a substantial reduction in total life cycle emissions in hydrogen production from underground coal gasification. Kalinci et al. [6] performed a life cycle assessment of hydrogen production from CFBG/DG biomass production in order to use the generated hydrogen in PEM fuel cell vehicles by investigating the costs of GHG emissions reduction. The extreme energy consumption rates were observed in the compression and transportation of hydrogen steps for the CFBG based system. Zamfirescu and Dincer [7] reported a few possible occasions and benefits of using ammonia as a sustainable fuel in transportation vehicles. They have compared ammonia with other conventional fuels in different aspects. Moreover, using ammonia both as a refrigerant and a fuel, they calculated refrigeration effect with respect to refrigeration power vs engine's power ending up with that ammonia is the cheapest fuel on $/GJ basis.

Nuclear based thermochemical hydrogen production has received a huge attention in recent years. Ozbilen et al. [8] conducted comparative LCA study for Cu–Cl water-splitting cycle in comparison with the sulphur iodine (S-I) water splitting cycle and high temperature water electrolysis. They found that steam methane reforming (SMR) method has about 12 times more global warming potential (GWP) than nuclear Cu–Cl cycle for hydrogen production. Although the production capacity doubles, the GWP value does not double because of initial construction and setup contribution. In another study [9], they found out that higher hydrogen production plant capacity lowers the total GWP value. The four-step Cu–Cl thermochemical water decomposition cycle has lower environmental influences than the three- and five-step cycles due to its lower energy requirements. Cetinkaya et al. [10] studied comprehensive life cycle assessment for five different methods of hydrogen generation including steam reforming of natural gas, coal gasification, water electrolysis via wind and solar, and thermochemical water splitting with a Cu–Cl cycle. They resulted that the most environmentally benign method is wind electrolysis based hydrogen production, which is then followed by solar PV based electrolysis process. Both of the renewable energy methods can be utilized in suitable locations with low capacities. Dong et al. [11] considered various routes for hydrogen production such as gasoline reforming, diesel reforming, natural gas reforming, soybean-derived biodiesel, reforming, and waste cooking oil-derived biodiesel reforming in terms of environmental impact.

In addition, life cycle assessments of electricity production methods, including nuclear option, have been performed in the open literature. Lenzen [12] prepared a review of nuclear energy for electricity production and compared with other alternative options such as solar, wind and hydroelectric. They found that greenhouse gas emissions for LWR and HWR of between 10 and 130 g CO_2 eq/kWh_{el}, with an average of 65 g CO_2 eq/kWh_{el} which is quite lower value compared to fossil fuels in the range of 600–1200 g CO_2 eq/kWh_{el}. Yildiz and Recently, Walker et al. [13] performed economic and environmental analyses for hydrogen production via bitumen upgrade for Ontario province in Canada. This is a promising opportunity to integrate oil sands into hydrogen and ammonia production. In the study by Utgikar and Thiesen [14], the GWP of high temperature electrolysis was found to be about 2 kg CO_2 per kilogram of hydrogen produced corresponding to one sixth of SMR method. It was also shown that high temperature electrolysis plant efficiency connecting with high temperature gas cooled reactor can yield over 53% hydrogen production efficiency at 800 °C operation [15]. Acar and Dincer [16] performed an extensive study for economic, environmental and social impacts of various hydrogen production methods. Ammonia is also a favorable candidate to be used in cooling systems as it has been studied by many researchers [17,18]. Ammonia synthesis can also be combined with solar thermal power plants by considering the heat recovery options [19]. Hussain et al. [20] also performed a comparative life cycle analyses for some biofuels and other conventional fuels.

A few of the available ammonia utilization pathways can be listed as follows [21]:

- Direct feed of ammonia into an internal combustion engine
- Ammonia thermal cracking and feed of the products (H_2 and N_2) all together in the internal combustion engine cylinder for combustion
- Separation of N_2 and H_2 streams simultaneously with the decomposition such that only pure H_2 is combusted; and the nitrogen is expanded for work production

- Direct ammonia high-temperature fuel cell systems,
- Ammonia thermal cracking and separation and further using the hydrogen into high temperature fuel cells
- Ammonia electrolysis and hydrogen used in proton exchange fuel-cells with additional exploitation of ammonia's refrigeration effect

Note that ammonia is also a suitable fuel for spark-ignition engines because of its high opposition to auto ignition. On the other hand, it is of great interest to utilize ammonia in compression-ignition engines due to the popularity of compression ignition engine-driven electricity generators. For internal combustion engines, service network is already available and ready in addition to mature manufacturing technology.

In this study, nuclear energy based ammonia production options ranging from thermochemical cycles to high temperature electrolysis are comparatively evaluated using life cycle assessment (LCA) tool. In order to show the significant difference with conventional ammonia production, the results for steam methane reforming are also given. The specific objectives of the present study can be written as follows: to conduct a life cycle assessment of various nuclear energy based ammonia production pathways, to determine environmental impacts of nuclear based ammonia production routes in global warming potential, human toxicity, abiotic depletion, acidification, terrestrial ecotoxicity and stratospheric ozone layer depletion.

Systems description

In the present study, five different ammonia production methods are selected for comparative assessment purposes as illustrated in Fig. 1 where the Haber–Bosch process is utilized for ammonia synthesis. There are mainly two main techniques for nuclear hydrogen production, namely, nuclear water splitting and thermochemical cycle. The water splitting via nuclear electricity can also be achieved by electrolysis. The nuclear electricity can be directly used in an electrolysis unit for hydrogen production or nuclear process/waste heat can be utilized for high-temperature steam electrolysis process couple with nuclear electricity. Thermochemical water-splitting cycles denote technical processes which decompose the water molecule while the separate streams of hydrogen and oxygen gases are released via a closed system of chemical reactions. In addition to the chemical elements constituting the water molecule, the chemical composites in multi-step thermochemical water-splitting cycles include other components. For example, the copper–chlorine thermochemical cycle includes compounds of Cu and Cl whereas the sulfur–iodine thermochemical cycle includes chemical composites of S and I. In a thermochemical cycle, water is only consumed; the only products generated are hydrogen and oxygen as separated streams; and all other chemicals involved in particular reaction steps are completely recycled. The thermochemical plants are supplied only with heat and water to operate. In addition to pure thermochemical cycles, there are hybrid thermo-electro-chemical cycles which utilize a relatively small amount of electricity to drive some electrochemical reactions in addition to heat. Thermochemical cycles are considered a promising selection for large-scale hydrogen production which can be realized at nuclear reactor facilities. Therefore, Cu–Cl based nuclear thermochemical cycles with multiple steps are considered in this work.

Nitrogen production

For ammonia production, nitrogen is also needed. The cryogenic air separation is usually employed method for massive amount of nitrogen production which is used in this study. In the life cycle assessment of nitrogen production, electricity for process, cooling water, waste heat and infrastructure for air separation plant are taken into account. The allocation factors

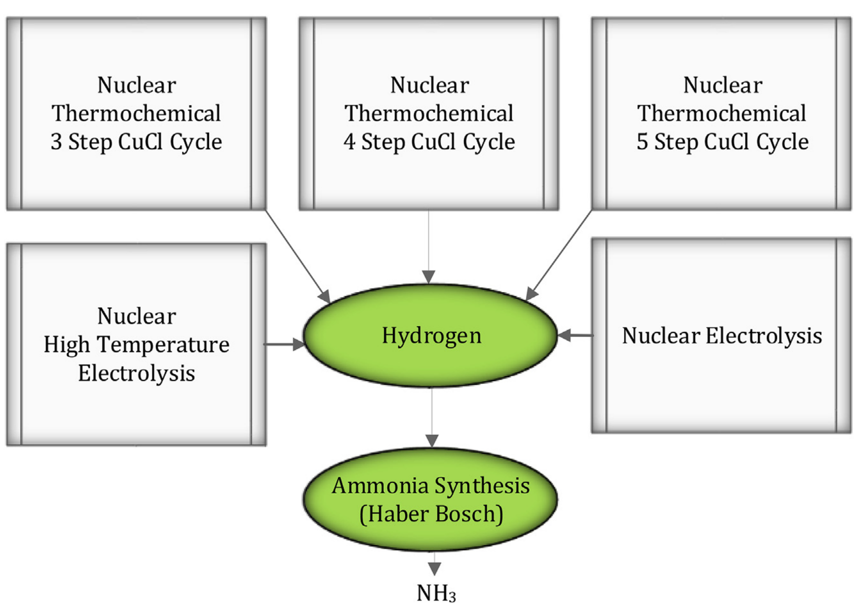

Fig. 1 – Selected nuclear based hydrogen and ammonia production methods.

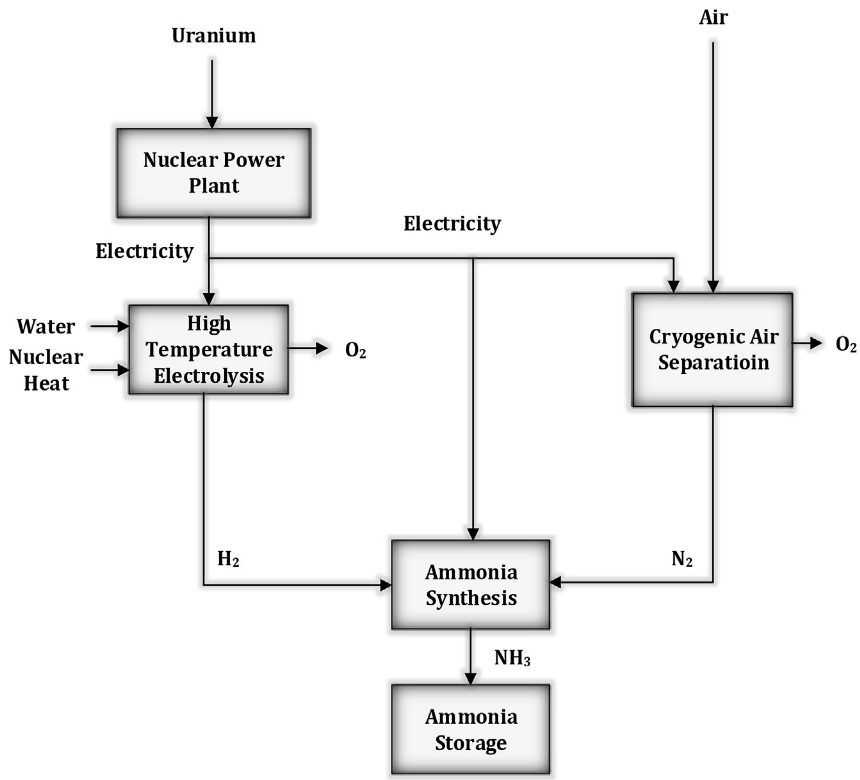

Fig. 2 – Nuclear high temperature electrolysis and Haber–Bosch process for ammonia production.

were obtained from the heat of vaporization and the specific heat capacity multiplied with the temperature difference from 20 °C to the boiling point. The utilized software, SimaPro, has the values of nitrogen production from cryogenic air separation process in the database [22].

Nuclear electrolysis methods

In nuclear-based high-temperature ammonia production, the system consists of a nuclear power plant, high temperature electrolyzer, cryogenic air separation unit and a Haber–Bosch synthesis plant as shown in Fig. 2. The required electricity is utilized from nuclear power plant and the required heat for high temperature electrolysis is supplied from nuclear waste heat. The main inputs of the nuclear high temperature electrolysis method are listed in Table 1. Nuclear power plant electricity is assumed as a mixture of 66.5% from pressure water reactor (PWR) and 33.5% from boiling water reactor (BWR) type reactors [22], since the SimaPro software database does not contain CANDU type reactors.

Table 1 – Main inputs for nuclear high temperature electrolysis method.

Parameter	Value	Unit
Hydrogen from nuclear high temperature electrolysis	1	kg
Water	9	kg
Electricity, nuclear	28.9	kWh
Nuclear heat	6.67	kWh

Nuclear based electricity yields lower cost and reliable supply. Combining nuclear power plant with ammonia production plant is an encouraging method. In high temperature electrolysis, the excess heat in the nuclear power plant is utilized to decrease the required amount of electricity for electrolysis as seen in Fig. 2. Besides, in nuclear electrolysis based option, electricity is produced in nuclear power plant and directly utilized in electrolysis coupled with Haber–Bosch ammonia synthesis loop. There is no heat assisting in this method. Hence, more electrical energy is required to split water into hydrogen and oxygen. The schematic diagram and main inputs of nuclear electrolysis based ammonia production option can be seen in Fig. 3 and Table 2.

Nuclear thermochemical methods

The copper–chlorine (CuCl) cycle is a multiple step thermochemical cycle for the production of hydrogen. The CuCl cycle is a combined process that employs both thermochemical and electrolysis steps. The CuCl cycle involves four chemical reactions for water splitting, whose net reaction decomposes water into hydrogen and oxygen. Both heat and electricity are provided at the same time for hydrogen generation and then hydrogen reacts with nitrogen to produce ammonia. Input of water and energy for the production of steam are included but other infrastructure is not included, as the heating infrastructure is already a part of the respective heating modules used in the plant. Nuclear power plant electricity is assumed as a mixture of 66.5% from PWR and 33.5% from BWR type reactors for this method, too [22]. The life cycle assessment includes fuel elements, chemicals, and diesel requirements as well as

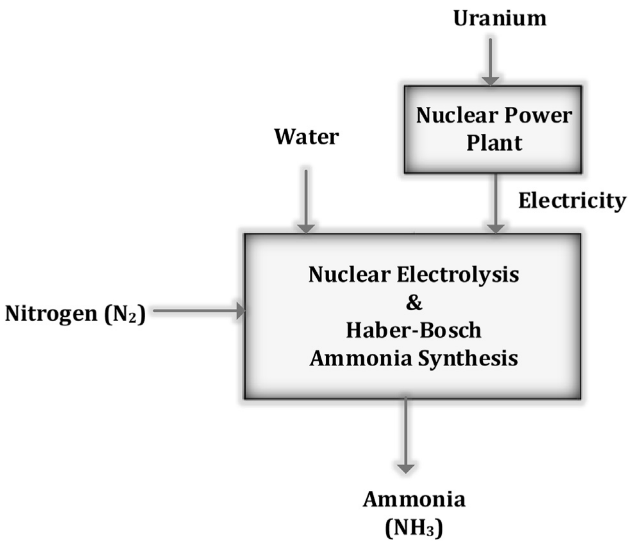

Fig. 3 – Energy and material nuclear electrolysis based ammonia production.

the relevant transport necessities. Water use for cooling is also taken into account. Considered radioactive waste streams are: spent fuel to reprocessing and conditioning; operational low active waste for conditioning in the intermediate repository; and, contaminated waste from dismantling. Non-radioactive wastes are taken into account. The average burnup relates to an average enrichment of 3.8% U235 for fresh uranium fuel elements in BWR type reactor [22]. The average burnup corresponds to an average enrichment of 4.2% U235 for fresh uranium fuel elements in PWR type reactor [22]. The diesel requirements for the yearly test of diesel emergency generators are accounted for. The transport requirements are calculated with the standard distances for chemical and diesel requirements and specific distances for fuel recharge and radioactive waste. The main inputs of the nuclear thermochemical cycles, which are taken from the open literature [8,9] are listed in Tables 3–5. Here, it is assumed that the excess heat in the nuclear plant is utilized in the hydrogen production process with an effectiveness of 90%. It is important the note that the waste heat used in the analyses does not source from any chemical plant heat but from nuclear excess heat. In this way, the total environmental impact for thermochemical cycles are lowered. A schematic diagram of energy and material flows of nuclear thermochemical CuCl cycle based ammonia production options are shown in Fig. 4. For ammonia production, additional electricity (rather than hydrogen and nitrogen production) required for the Haber–Bosch synthesis is also supplied from nuclear electricity as the main inputs are shown in Table 6.

Table 2 – Main inputs and outputs for nuclear electrolysis method.

Parameter	Value	Unit
Hydrogen from nuclear electrolysis (output)	1	kg
Water	9	kg
Electricity, nuclear, at power plant	53.5	kWh

Table 3 – Main inputs and outputs for nuclear 3 Step Cu–Cl cycle method.

Parameter	Value	Unit
Hydrogen from nuclear 3 Step Cu–Cl Cycle (output)	1	kg
Water	9	kg
Electricity, nuclear	67.15	MJ
Nuclear heat	325	MJ

Table 4 – Main inputs and outputs for nuclear 4 Step Cu–Cl cycle method.

Parameter	Value	Unit
Hydrogen from nuclear 4 Step Cu–Cl Cycle (output)	1	kg
Water	9	kg
Electricity, nuclear	67.15	MJ
Nuclear heat	289.89	MJ

Table 5 – Main inputs and outputs for nuclear 5 Step Cu–Cl cycle method.

Parameter	Value	Unit
Hydrogen from nuclear 5 Step Cu–Cl Cycle (output)	1	kg
Water	9	kg
Electricity, nuclear	50.3	MJ
Nuclear heat	352.26	MJ

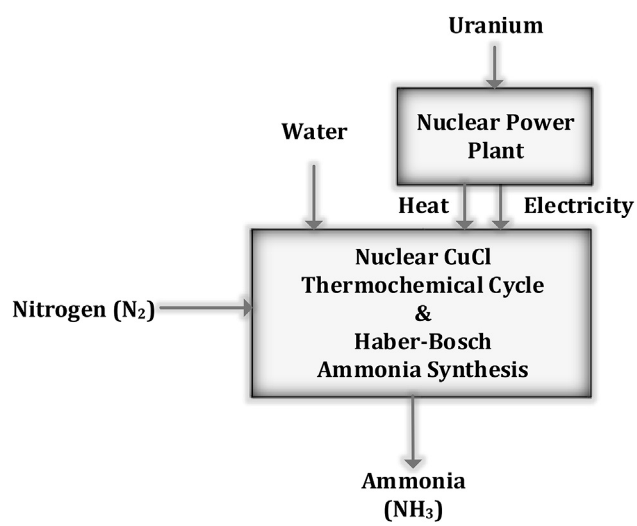

Fig. 4 – Energy and material flows of nuclear CuCl cycle based ammonia production.

Table 6 – Main inputs and outputs for ammonia production process.

Parameter	Value	Unit
Ammonia (output)	1	kg
Nitrogen	0.823	kg
Hydrogen	0.177	kg
Electricity, nuclear (additional)	2	kWh

Life cycle assessment (LCA)

LCA is a methodology from cradle to grave. This tool helps to make effective decision by analyzing the system systematically. LCA analyses the environmental impact of a product or process over the length of its entire life, beginning from raw material extraction to final disposal. LCA deliberates all the life periods of product or process to assess the overall environmental impact. There are a number of assessment methods progressed over the time to categorize and characterize the environmental flows of system. In this study, LCA is performed using CML 2001 method which was proposed by a set of scientists under the principal of CML (Center of Environmental Science of Leiden University) including a group of impact classes and characterization procedures for the impact assessment phase in 2001 [22]. The environmental impact categories considered in this study are explained as follows:

The key concern of depletion of abiotic resources category is the human and ecosystem health that is affected by the extraction of minerals and fossil as inputs to the system. For each extraction of minerals and fossil fuels, the Abiotic Depletion Factor (ADF) is defined. This indicator has globe scale where it is related with concentration reserves and rate of de-accumulation [22]. The toxic substances on the human environment are the core concerns for this category. In the working environment, the health risks are not included in this category. The characterization factors, such as Human Toxicity Potentials (HTP), are determined with (The Uniform System for the Evaluation of Substances) USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon. 1,4-dichlorobenzene equivalents/kg emissions is used to express each toxic substance. Depending on the substance, the geographical scale differs between local and global indicator [22]. Due to the stratospheric ozone depletion, a bigger portion of UV-B radiation spreads the world surface. It may have damaging properties upon human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and on materials. The category is output related and it is at global scale. The model of characterization is advanced by the World Meteorological Organization (WMO) and describes ozone depletion potential of various gasses in unit of kg CFC-11 equivalent/kg emission. The geographic scope of this indicator is at global scale and the span of time is infinity [22]. Many chemical substances may cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials. RAINS 10 model is used to calculate the Acidification Potential (AP) for emissions to air, describing the fate and deposition of acidifying substances. The Regional Air Pollution Information and Simulation (RAINS) model is a European-scale integrated assessment model dealing with air quality and associated effects. SO_2 equivalents/kg emission is utilized to state the AP. This category has a different geographical scale that can be local and global. Depending on the availability the characterization aspects containing fate were used. But, when not available, the aspects used without fate (In the CML baseline version only factors including fate were used). The method was stretched for nitric acid, water, soil, and air; sulphuric acid, water; sulphur trioxide, air; hydrogen chloride, water, soil; hydrogen fluoride, water, soil; phosphoric acid, water, soil; hydrogen sulphide, soil, all not including fate. Nitric oxide, air (is nitrogen monoxide) was added containing fate [22]. The greenhouse gases to air are associated with the climate change. Adversative effects upon ecosystem health, human health and material welfare can result from climate change. The Intergovernmental Panel on Climate Change (IPCC) developed the characterization model which is selected for the development of characterization factors. A kg carbon dioxide/kg emission is used to express the Global Warming Potential for time horizon 500 years (GWP500). This indicator has a global scale [22]. Terrestrial ecotoxicity category refers to impacts of toxic substances on terrestrial ecosystems as a result of emissions of toxic substances to air, water and soil. Ecotoxicity Potential (FAETP) is calculated with USES-LCA, describing fate, exposure and effects of toxic substances. The time horizon is infinite. The characterization factors are expressed as 1,4-dichlorobenzene equivalents/kg emission. The indicator applies at global/continental/regional and local scale [22].

Results and discussion

The overall environmental impact of any process is not complete if only operation is considered, all the life steps from resource extraction to disposal during the lifetime of a product or process should be considered. Mass and energy flows and environmental impacts related to plant construction, utilization, and dismantling stages are taken into account in LCA analysis [23,24]. Using SimaPro software for life cycle analysis, cradle to grave considerations of various nuclear based ammonia production methods are investigated and comparatively assessed.

Various nuclear resources based ammonia production pathways are determined, and the energy and material requirement for each route are identified and calculated. The values are used in SimaPro software for the calculations of life cycle assessment. The calculations are based on one kg of ammonia and hydrogen end product since the functional unit is one kg ammonia and hydrogen. The environmental impact results are presented herein.

Hydrogen production results

In order to provide a comparison per unit of hydrogen production, the environmental impacts of one kg hydrogen production from selected methods are comparatively shown in Figs. 5 and 6 for abiotic depletion and global warming categories. The high temperature electrolysis via nuclear energy has the lowest impact while nuclear five step thermochemical cycle has the highest impact. However, in comparison with SMR method, nuclear options are significantly environmentally friendly. The GHG emissions from nuclear high temperature electrolysis and five step CuCl cycle correspond to 0.5 kg CO_2 eq. and 1.37 kg CO_2 eq., respectively. The natural gas is treated as the fundamental contributor for steam methane reforming corresponding to about 0.116 kg Sb eq. per kg hydrogen in abiotic depletion category. Although the nuclear thermochemical cycle is a cleaner method than steam methane reforming, almost 33% of GHG emissions for nuclear

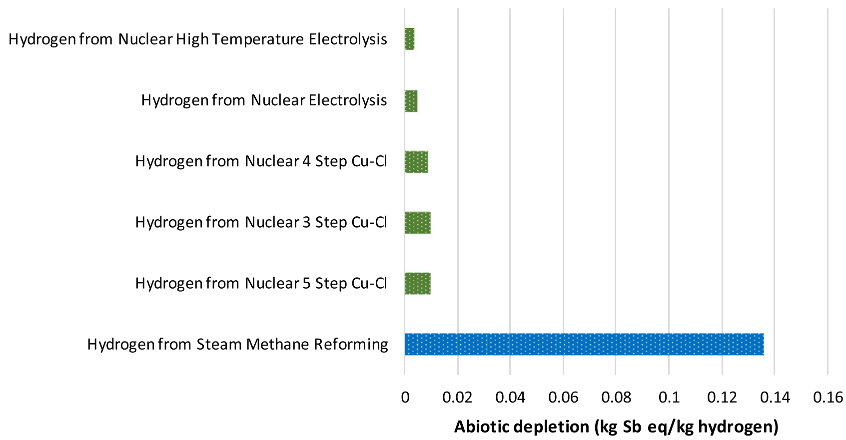

Fig. 5 – Abiotic depletion values of nuclear based hydrogen production methods.

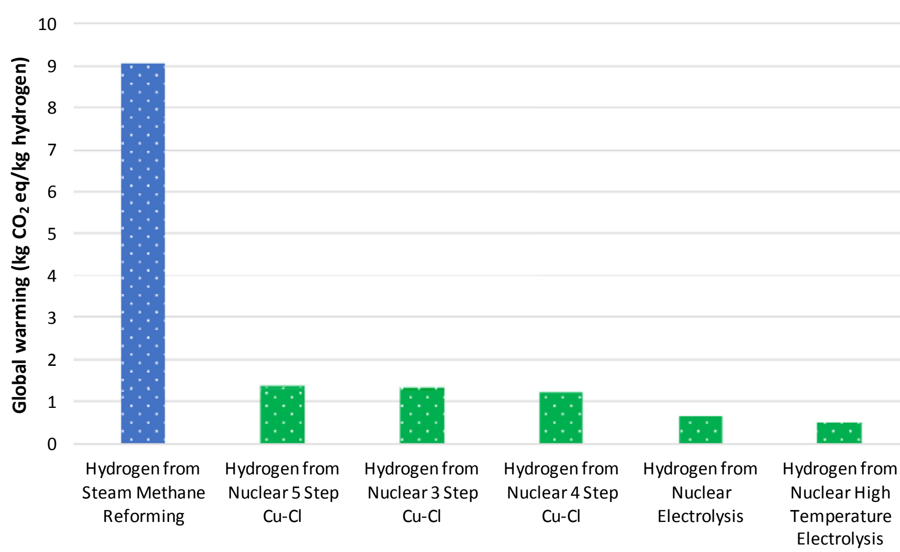

Fig. 6 – Global warming values of nuclear based hydrogen production methods.

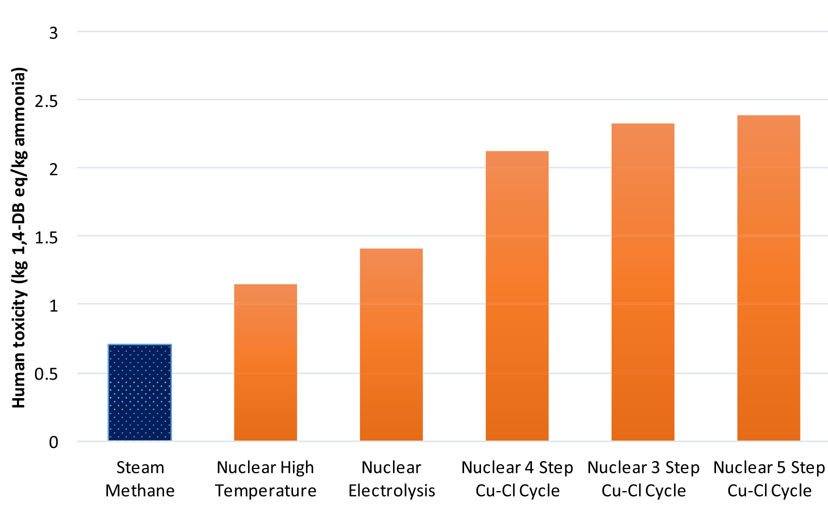

Fig. 7 – Human toxicity values of nuclear based ammonia production methods.

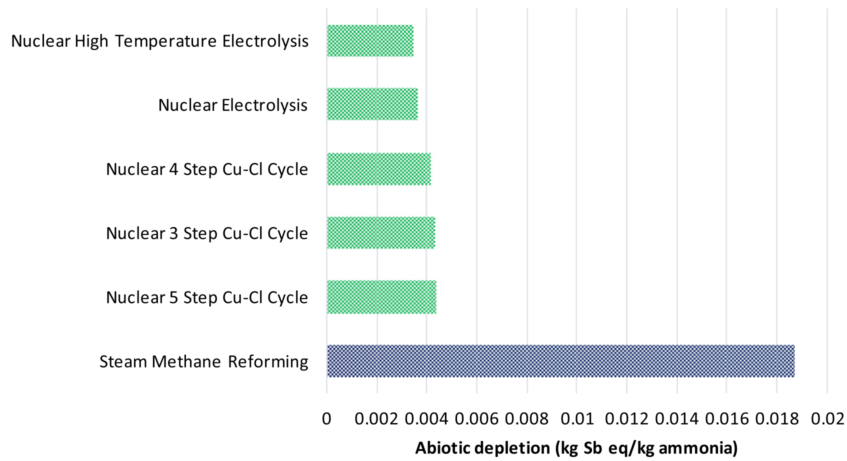

Fig. 8 – Abiotic depletion values of nuclear based ammonia production methods.

3 step Cu–Cl based hydrogen production derives from hard coal burned in power plant. This is mostly used in uranium enrichment plants.

Ammonia production results

The impact on human health due to human toxicity is maximum for the ammonia production from nuclear five step thermochemical cycle where it corresponds to 2.39 kg 1,4-DB-eq per kg of ammonia. Ammonia from nuclear based electrolysis methods yield lower human toxicity values where the lowest is for high temperature electrolysis with a value of 1.15 kg 1,4-DB-eq as seen in Fig. 7. Conversely, SMR method is less toxic than other methods which is the case only for this category. This is due to the high amount of uranium tailings disposal process in nuclear options where it corresponds to 84.9% contribution to human toxicity value of five step nuclear CuCl cycle. In our recent study [25] for conventional resources based ammonia production, the human toxicity values of Cu–Cl thermochemical cycles are slightly lower than nuclear electrolysis methods because of selected heat source and waste heat utilization efficiency. As explained previously, here we assume nuclear power plant waste heat with a utilization efficiency of 90% for Cu–Cl thermochemical hydrogen production methods.

The abiotic resources are natural resources including energy resources, such as iron ore and crude oil, which are considered as non-living. The abiotic depletion is highest for nuclear five step CuCl cycle method with a value of 0.043 kg Sb eq. as it is illustrated in Fig. 8. Besides, nuclear high temperature electrolysis based option has the lowest abiotic depletion corresponding to 0.0034 kg Sb eq. The main source of abiotic depletion for nuclear based methods is the hard coal mining which is used in the process of power generation for the uranium enrichment plant. The contribution of nitrogen production at plant is 60.4% whereas it is 39.6% for hydrogen production from nuclear five step CuCl cycle to the abiotic depletion values of five step thermochemical cycle. In nuclear-based high-temperature electrolysis method for ammonia production, 72.8% of overall abiotic depletion is

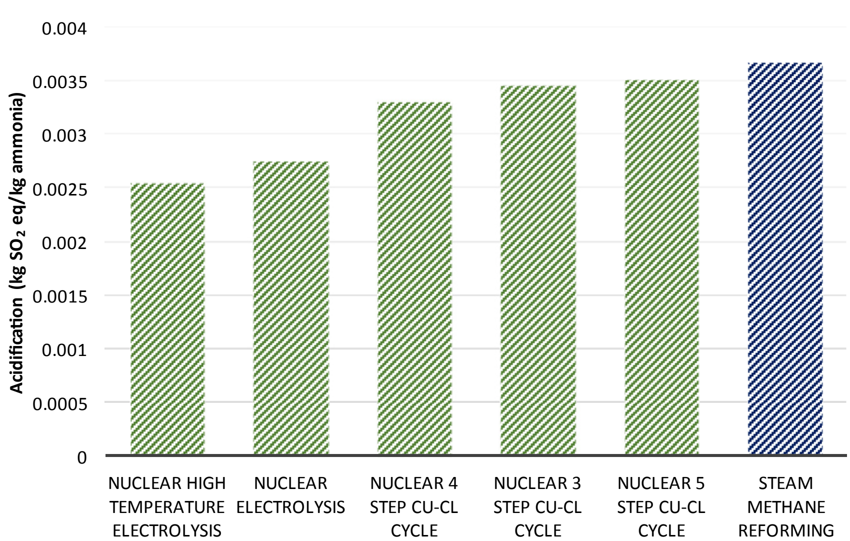

Fig. 9 – Acidification values of nuclear based ammonia production methods.

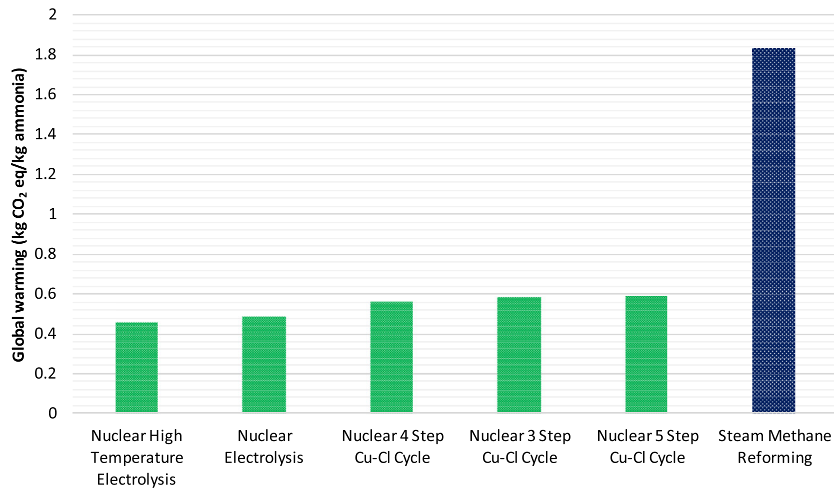

Fig. 10 – Global warming values of nuclear based ammonia production methods.

caused by hydrogen production whereas only 7.2% of the abiotic depletion value is originated from nitrogen production.

The acidification values are lowest for nuclear high temperature electrolysis based option (0.0025 kg SO_2 eq.) followed by nuclear electrolysis method (0.0027 kg SO_2 eq.) as shown in Fig. 9. It is higher in thermochemical cycles because of used chemical substances. 51.5% of the acidification value is sourced from hydrogen production process in entire ammonia production process. 3.8% enriched uranium in fuel element for LWR at nuclear fuel fabrication plant represents the 29.6% of overall life cycle acidification value.

In terms of global warming potential, nuclear high temperature electrolysis option yields the lowest environmental impact with a value of 0.46 kg CO_2 eq. GHG emission. It is quite similar for thermochemical cycles corresponding to about 0.58 kg CO_2 eq per kg ammonia. However, it is very high (1.83 kg CO_2 eq.) for the conventional SMR based ammonia production as shown in Fig. 10. Cu–Cl thermochemical based ammonia production options yield lower global warming potentials than our previous study [25] because, here we calculate the nuclear waste heat based on electricity production of the power plant. The heat output from the nuclear plant is taken as 62% of electricity output [8,9]. Also, a heat utilization efficiency of 90% is assumed. High heat utilization efficiency decreases the ecological foot print of Cu–Cl thermochemical cycles. Similarly, for high temperature nuclear electrolysis method, having higher heat recovery efficiency slightly decreases the GHG emissions compared to nuclear electrolysis in this study. Furthermore, nuclear high temperature electrolysis yields lower global warming than our previous study [26] due to increase in heat recovery efficiency from the plant. Most of the GHG emissions (75%) from nuclear electrolysis based ammonia production options are caused by nitrogen production since it consumes high amounts of electricity. The uranium enrichment process is also quite energy consuming causing high GHG emissions. The contribution of nitrogen production process decreases to 59.4% for three step CuCl cycle. It is mainly due to the electricity grid mix is used for cryogenic nitrogen production plant. Nuclear electrolysis options have approximate values with many renewable based ammonia production options found in the literature [26].

The ozone layer depletion is currently an important issue which needs to be decreased. In terms of ozone depletion, nuclear high temperature electrolysis yields lowest

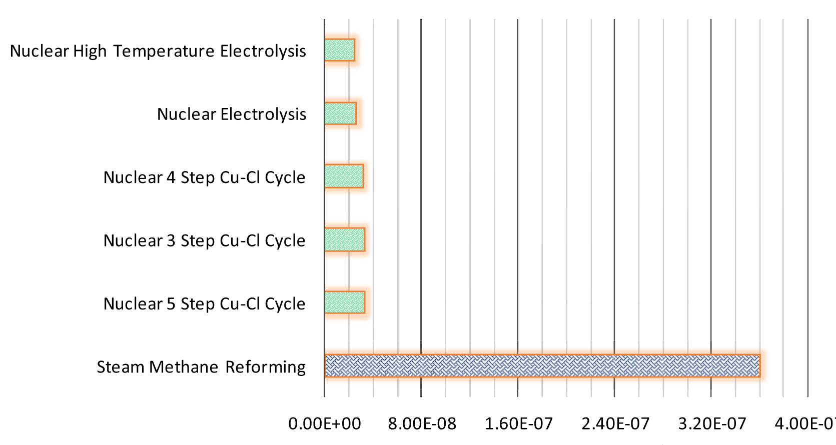

Fig. 11 – Ozone layer depletion values of nuclear based ammonia production methods.

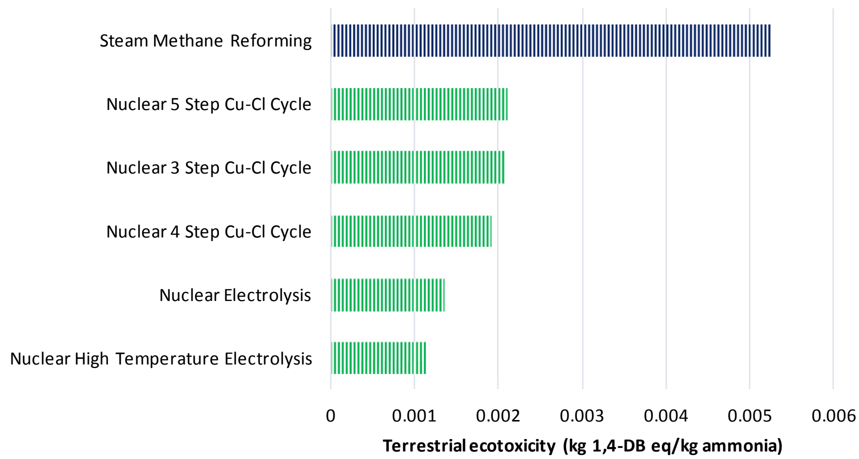

Fig. 12 – Terrestrial ecotoxicity values of nuclear based ammonia production methods.

Table 7 – Fuel consumption and driving cost of various fueled vehicles including hydrogen and ammonia.

Fuel/source	Fuel consumption (kg/km or kWh/km)	Fuel market price (US$/kg or US$/kWh)
Gasoline	0.06491	1.00
CNG	0.06039	0.80
LPG	0.05763	0.82
Hydrogen	0.01955	2.30
Electric vehicle	0.21670	0.15
Ammonia	0.11080	0.28

environmental impact corresponding to 2.39E-08 kg CFC-11 eq. as shown in Fig. 11. The other methods have approximately same values where nuclear five step CuCl cycle represents a value of 3.32E-08 kg CFC-11 eq. per kg of ammonia. They are mainly caused by the transportation of fuels namely natural gas and crude oil where they are used for electricity production mix and also in uranium conversion plants. More than 50% of ozone layer depletion value for nuclear CuCl cycle based ammonia production options is sourced from long distance transportation of natural gas via pipelines. For the high-temperature nuclear electrolysis method, almost 35% of ozone layer depletion is caused by long distance natural gas transport whereas 15% is originated from crude oil transport.

Considering the terrestrial ecotoxicity category, five step nuclear Cu–Cl cycle results the highest among other nuclear options, however, the environmental impacts are still significantly lower than conventional SMR method as comparatively shown in Fig. 12. The reason of ecotoxicity for all nuclear options is mainly non-radioactive emissions because of the uranium tailings disposal. It has about 75% contribution to this category for thermochemical cycles whereas it is lower for nuclear electrolysis methods. The heavy fuel oil burned in industrial furnace is the second highest contributor in this category for nuclear high temperature electrolysis based ammonia production. The main elements causing ecotoxicity are primarily vanadium and mercury.

In order to examine the practicality of various fuels for the transportation sector in terms of cost assessment, the fuel consumption and market prices (see Table 7) are considered for the driving cost calculations in Fig. 13. The market prices are based on the current production methods, hence steam methane reforming is the pathway for ammonia and hydrogen. Ammonia vehicle represents the lowest cost driving per 100 km range as illustrated in Fig. 13. Although having higher specific heating value, hydrogen cost is quite higher because of higher unit cost. By developing technologies such as renewable options, this cost will decrease and compete with electric and LPG vehicles.

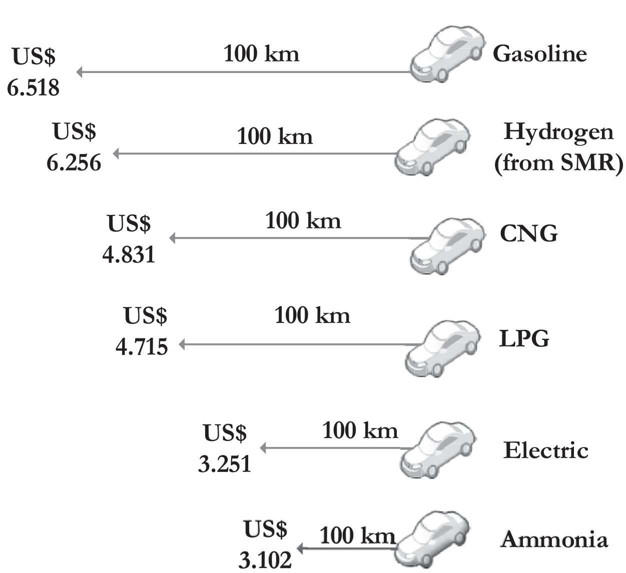

Fig. 13 – Driving cost of various fueled vehicles including ammonia and hydrogen for 100 km driving range.

Conclusions

A life cycle assessment of the nuclear based hydrogen and ammonia production methods is conducted and environmental impacts are comparatively assessed including the conventional steam methane reforming method. Furthermore, a driving cost assessment of various fueled vehicles including ammonia and hydrogen is presented for transportation sector. The following concluding remarks can be written for this study:

- Nuclear high temperature electrolysis yields the lowest overall impact in all selected categories promising an alternative pathway for ammonia production.
- In terms of human toxicity, nuclear five step CuCl cycle has the highest environmental impact among all nuclear options.
- Nuclear electrolysis based options yield lower abiotic depletion, global warming and ozone layer depletion values among all methods.
- Global warming potentials of nuclear electrolysis and nuclear high temperature electrolysis are slightly lower compared to thermochemical cycles however, significantly lower than conventional steam methane reforming method.
- By utilization of excess heat and electricity in nuclear power plants, hydrogen and ammonia can be produced in an environmentally benign manner.
- Nuclear based hydrogen and ammonia production is a promising option in terms of environmental impact.

Utilization of nuclear heat is considered to be a promising technique for hydrogen and hence ammonia production which may help lower the environmental impact of current natural gas based hydrogen and ammonia production. This study shows that nuclear electricity and heat can be used for ammonia production in a more environmentally benign manner. As a further study, thermoeconomic and thermodynamic analyses of the nuclear based ammonia production methods would bring enhanced insights for practicality of these processes.

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Nomenclature

BWR	Boiling water reactor
CCS	Carbon capture storage
CFBG	Circulating fluidized bed gasifier
CML	Center of environmental science of Leiden University
DG	Downdraft gasifier
FAETP	Eco-toxicity potential
GHG	Greenhouse gas
GWP	Global warming potential
HHV	Higher heating value
HTP	Human toxicity potentials
IPCC	Intergovernmental panel on climate change
LCA	Life cycle analysis
LPG	Liquefied petroleum gas
PV	Photovoltaic
PWR	Pressurized water reactor
SMR	Steam methane reforming
UCG	Underground coal gasification
USES	Uniform system for the evaluation of substances
WMO	World meteorological organization

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