Green ammonia enables sustainable energy production in small island developing states: A case study on the island of Curaçao

Victor N. Sagel, Kevin H.R. Rouwenhorst, Jimmy A. Faria *

Catalytic Processes and Materials Group, Faculty of Science and Technology, MESA+ Institute for Nanotechnology, University of Twente, PO Box 217, 7500 AE, Netherlands

A R T I C L E   I N F O

Keywords:
Green ammonia
Small island developing states (SIDS)
Caribbean
Absorption enhanced haber bosch (AEHB)
Zero liquid discharge desalination (ZLDD)
Power-to-Ammonia-to-Power (P2A2P)

A B S T R A C T

Small Island Developing States (SIDS) have a high dependency on fossil fuels for energy, water, and food production. This has negative implications on the carbon footprint and resilience of the SIDS. Wind power is one of the most promising options for renewable energy in the coastal areas of the SIDS. To account for the seasonal intermittent nature of wind energy, ammonia can be used for energy storage. In this paper, ammonia as an energy vector, is examined to reduce the costs and carbon footprint of energy on the island of Curaçao as a showcase for Caribbean SIDS. The levelized cost of electricity (LCOE) for the combined wind and ammonia energy storage system is 0.13 USD/kWh at a discount rate of 5%. This is cost competitive with the LCOE of 0.15–0.17 USD/kWh from heavy fuel oil, which is the main electricity source in the Caribbean SIDS. In Curaçao, the LCOE from LNG and coal without carbon capture and storage (CCS) is 0.07–0.10 USD/kWh and 0.09–0.14 USD/kWh, respectively. When CCS is applied, the LCOE from LNG and coal is 0.10–0.13 USD/kWh and 0.14–0.21 USD/kWh, respectively. This suggests that the LCOE of the combined wind and ammonia energy storage system can be competitive with fossil-based alternatives with carbon capture and storage (CCS) in a decarbonized energy landscape. The CO₂-footprint of the combined wind energy and ammonia energy storage system is 0.03 kg CO₂/kWh, compared to 0.04 kg CO₂/kWh and 0.12 kg CO₂/kWh for LNG-/coal-based energy generation with CCS, respectively.

1. Introduction

Building resilience in our energy systems is a fundamental challenge, especially for Small Island Developing States (SIDS) under changing climate conditions [1]. The average electricity price for the SIDS in the Caribbean area is ca. 0.35 USD/kWh [2–6], which is substantially higher than those in mainland US at ca. 0.10 USD/kWh [7], and Europe at ca. 0.22 USD/kWh [10,11]. It should be noted that these are consumer prices, rather than production costs. While many of these islands have drafted national plans to achieve the United Nations Sustainable Development Goals (UN-SDG) [12,13] and are part of the SIDS Accelerated Modalities of Action (SAMOA) pathway [14], the large investments and complex technologies required for transforming the islands in self-sustained regions greatly hinder the implementation pace [14–17]. Clearly, cost-effective technologies are required to empower the Caribbean islands, and more broadly SIDS, for the sustainable production of fresh water, food, and energy, as outlined in the UN-SDG and SAMOA plans [9].

Solar and wind energy utilization factors in the Caribbean region are rather significant. The share of renewable energies in the electricity grid, however, is typically low, resulting in large expenditures for fossil fuels [20,21]. Some Caribbean islands spend nearly half of their exports revenues on energy generation [2]. Tapping on renewable resources such as solar and wind energy is key for more sustainable, reliable, and affordable development [18]. The challenge is that renewable solar and wind energy is fluctuating in nature, and often the peaks in energy generation are out of phase with the peaks in demand, both on daily and on seasonal basis throughout the day and year, respectively [19,22]. Therefore, energy storage is required. For day-night operation, short-term or daily energy storage using batteries is the most attractive solution with a round-trip efficiency (RTE) of ca. 85% [23]. In contrast, long-term energy storage is mostly feasible using power-to-chemical conversion routes [10] by transforming electricity into hydrogen via electrolysis (Fig. 1a). While converting this hydrogen into electricity...
again can result in a round-trip efficiency of ca. 25–40% [10], its safe storage and distribution is costly and cumbersome. Therefore, conversion of hydrogen into energy carriers is an attractive alternative for long term storage. The significant benefit of ammonia as an energy carrier is presented in Table 1.

Carbon-based energy carriers such as methane and methanol have also been proposed. However, these vectors require a sustainable and affordable carbon source [25]. Currently, direct air capture of CO \(_2\) from the atmosphere is not cost effective with costs of 250–500 USD/t [26], partially due to the low concentration of CO \(_2\) in the atmosphere.

In this regard, ammonia (NH\(_3\)) is considered as a carbon-free alternative, requiring abundant atmospheric nitrogen (N\(_2\)) [10]. Transforming hydrogen into ammonia is a necessary step to reduce the final cost of highly fluctuating renewable electricity in a completely green energy system [28]. Up to the 1990s, ammonia production via the Haber-Bosch process (350–500 °C and 100–400 bar) with electrolysis-based hydrogen production was operated at large-scale (350 t-NH\(_3\) d\(^{-1}\), equivalent to about 165 MW), proving the technology readiness for implementation [28,29]. Furthermore, costs of green ammonia are expected to decrease significantly, to values below 500 USD/t (estimated range of 222–480 USD/t) upon widespread implementation around the world in 2040 [31], improving the long term projection of green ammonia-based energy storage.

At the small scales of a few MWs required in SIDS (typically a few 100 kg-NH\(_3\), h\(^{-1}\)), the high operating temperature and pressure of the Haber-Bosch synthesis loop results in significant heat losses (Fig. 1b) [8,32-34]. Thus, milder conditions in the ammonia synthesis loop are required for effective scale-down to a few MWs [35].

The pressure of a Haber-Bosch plant can be reduced by an order of magnitude upon introducing an absorbent for ammonia separation (absorbent enhanced Haber-Bosch or AEHB) [8,36]. Implementing such process may decrease the energy consumption of the ammonia synthesis loop, while also allowing improved intermittent operation [8]. Recently, Ruthenium-based ammonia synthesis catalysts gained renewed interest [37] [-] [40] given the significant catalytic activity and stability of these materials at temperatures as low as 250 °C [37]. Combining these catalysts with absorption-enhanced Haber-Bosch ammonia synthesis (AEHB) results in operation under relatively mild conditions of 250–400 °C and 10–30 bar [8].

In this work, a conceptual process is presented that employs renewable electricity from wind to generate hydrogen using an alkaline electrolyzer combined with batteries that is followed by an absorption-enhanced Haber Bosch (AEHB) synthesis loop for ammonia production with large-scale ammonia storage. Solid oxide fuel cells are utilized to generate on-demand renewable electricity from the stored ammonia for the electricity grid. This system is coupled to a novel process design based on zero-liquid discharge (ZLD) hybridized seawater desalination that leverages low- and high-rejection membranes in combination with mechanical vapor compression (MVC) to generate fresh water and solid salts (see section 2 of SI), avoiding the production of polluting brine effluents. Subsequently, the application of these technologies is studied for the island of Curacao as archetypal SIDS for ammonia-based energy storage in the Caribbean region.

Finally, the levelized cost of electricity (LCOE) and CO\(_2\)-footprint are benchmarked against heavy fuel oil-, natural gas-, coal-based energy production, either with and without 90% carbon capture and storage (CCS). The results indicate that an LCOE of 0.13 USD/kWh (discount rate of 5%) can be achieved for the combined wind and ammonia energy storage system. This design outperforms the LCOE of heavy fuel oil (0.14–0.17 USD/kWh), which is the current electricity source in the Caribbean region. Notably, the LCOE from LNG and coal in this location without carbon capture and storage (CCS) is 0.07–0.10 USD/kWh and 0.09–0.14 USD/kWh, respectively. When CCS is applied, the LCOE from LNG and coal increases to 0.10–0.13 USD/kWh and 0.14–0.21 USD/kWh, correspondingly. The CO\(_2\)-footprint of the combined wind energy and ammonia energy storage system is 0.03 kg CO\(_2\)/kWh, compared to 0.04 kg CO\(_2\)/kWh and 0.12 kg CO\(_2\)/kWh for natural gas- and coal-based energy generation with CCS, respectively. These promising results substantiate the utilization of green ammonia to unlock the potential of SIDS for sustainable production of renewable energy.

Table 1

| Processes                 | Hydrogen (€/kg H\(_2\)) | Ammonia (€/kg H\(_3\)) |
|--------------------------|--------------------------|------------------------|
| Production               | 2.70                     | 3.40                   |
| Transport                | 1.69                     | 0.17                   |
| Storage 1 day            | 0.71                     | 0.03                   |
| Storage 182 days         | 13.48                    | 0.49                   |

Fig. 1. Technology benchmarking of energy storage (a) edited from Ref. [10], and energy footprint of electrolysis-based Haber-Bosch (b) edited from Ref. [8].

2. Methodology

In this study, Curacao is selected as the prototypical location for tropical SIDS. This island has significant potential for wind energy, and already has 30 MW of installed capacity [5]. In this analysis, the storage capacity for short-term and seasonal energy storage was estimated (Section 1 of the Supporting Information - SI). The sizing of the wind farm was assessed using the electricity consumption of the island and the annual profiles of the wind velocity (see Section 1 of the SI). Renewable ammonia is produced from wind energy for improved grid reliability. The capacity of the water electrolyzers, batteries, ammonia plant, storage and ammonia-to-power conversion units were determined using the round-trip efficiencies (RTE) for short-term and long-term energy.
storage via batteries and ammonia required to satisfy the monthly electricity demand. The ammonia plant was modelled using ASPEN Plus. The resulting plant capacity was employed to determine the specific energy consumption (SEC) and equipment size for estimating the capital and operational costs. Finally, a seawater desalination plant was designed to supply freshwater for electrolysis using a unique combination of high- and low-rejection seawater reverse osmosis desalination membranes in combination with a mechanical vapor compression (MVC) that allows zero-liquid discharge desalination.

The carbon footprint was estimated by adjusting previously reported Life Cycle Analyses (LCAs) for SOFC and SOFC maintenance [41], windmill based green ammonia [42,43], wind powered P2A2P SOFC systems [44], and the carbon footprint of windmills [45], to fit the system herein described. The carbon footprint was subdivided in three contributions, these are Power to Ammonia, Ammonia to Power, and direct windmill power carbon footprints. The carbon footprint of P2A2P was then compared to other electricity generating processes, with- and without carbon emission taxes.

As shown in Fig. 2, the conceptual design considers generation of on-demand electricity for the islanded community over the entire year. In the months with excess wind electricity generation (Fig. 2a) the energy is stored in the form of ammonia, which is then consumed during the months with deficient renewable energy production (Fig. 2b). To stabilize the P2A2P process for daily fluctuations, short term energy storage is also in place (<1 day). For this task, conventional batteries are suitable as shown in Fig. 1a. As presented in Table 1, battery storge is a better option for small, short term storage as the round trip efficiency of batteries (ca. 85%) [23] is significantly higher than that of chemical storage in the form of hydrogen gas (25–40%) [10].

2.1. Renewable energy source

There are multiple options for sustainable energy generation on Curaçao. A previous study on Barbados, another Caribbean island, showed that wind energy is the renewable energy source with the lowest cost in the Caribbean [46]. This is in line with the 30 MW offshore wind capacity already in place on Curaçao [5]. Notably, Curaçao has very strong and consistent wind, which means that the net capacity factors of wind farms can reach values as high as 0.61 in this location [22]. Thus, this value will be used in this analysis.

2.2. Short-term and seasonal storage

The wind production capacity fluctuates daily and seasonally. Hence, the energy production is not necessarily in line with energy consumption profiles (Fig. 5). In order to estimate the total wind capacity required in a combined wind and ammonia energy storage system, round-trip efficiencies for short-term energy storage in batteries and for seasonal energy storage in ammonia must be accounted for.

The short-term fluctuations in wind energy can be solved using battolysers [23]. Battolysers combine a Ni–Fe battery and alkaline electrolyzer functionality in a single unit [23]. The battolysers are alkaline electrolyzers in combination with a Ni/Fe-redox battery. This device works on the principle that the batteries will be charged when they are not at full storage capacity. When the batteries are fully charged, the system will start producing hydrogen with the excess energy [23]. While the energy efficiency of this hybrid technology is not remarkable, it provides a cost-competitive solution for short-term energy storage and hydrogen generation [8]. For instance, these battolysers can store enough energy for a day and night cycle and work at a round-trip efficiency of up to 90% [23], however this analysis assumes the average measured efficiency of 85%. The round-trip efficiency of the power-to-ammonia-to-power process is 20.5% consisting of (1) battolysers for hydrogen production, (2) absorbent-enhanced Haber-Bosch (AEHB) process for ammonia synthesis, and (3) proton-conducting SOFC for energy generation. These round-trip efficiencies are similar to previously reported numbers [47]. As explained in Section 1 of the SI, the power-to-ammonia-to-power system was oversized according to the round-trip efficiency and the extent of wind energy fluctuation.

The short term energy storage system is designed to reduce the amount of process fluctuations required in the SOFC–H and AEHB systems. This helps to keep the grid consistent and limits the extent of degradation of these operation units. Once it becomes clear that windmill energy generation will remain low for longer than a day, SOFC–H’s can slowly increase capacity to support further energy generation.

To determine the energy storage requirements, wind data from
Curaçao has been used [22], while the correlation for energy output versus wind speed was taken from the Vestas V82 wind turbine (1.65 MW) [48]. The annual energy consumption of Curaçao was taken from WorldData as of April 2020 [49], and distribution throughout the months was based on the report of Argawala [50]. An iterative model was developed in Matlab (see section 1 of SI) to calculate the required installed wind capacity to generate sufficient energy for the entire year. This estimation included the required compensations for energy losses in battery storage and the P2A2P process.

3. Power-to-ammonia-to-power (P2A2P) system

As shown in Fig. 3, the power-to-ammonia-to-power process starts with wind energy. A bi-directional connection of the ammonia plant with the energy grid is considered, so that the battolysers can power the grid, but the grid can also power the ammonia plant to keep the system pressurized and heated when wind is low and the battolysers are discharged. The ammonia plant itself is powered by direct wind energy and stabilized by the battolysers. No back-up system is in place. However, additional ammonia capacity can be added from an external source.

At the start of the process, seawater flows into the plant to undergo demineralization to achieve a high purity in order to prevent damage to the electrolysers. The purified water is routed to the electrolysers where the electrochemical splitting is conducted to yield hydrogen and oxygen gas. The oxygen gas is released into the air, whereas the hydrogen is sent to the absorbent-enhanced Haber-Bosch (AEHB) reactor. A pressure swing absorber (PSA) unit is used to purify nitrogen gas from air. The resulting nitrogen stream is combined with hydrogen before entering the AEHB reactor. The ammonia synthesis reactor converts the hydrogen and nitrogen into ammonia, and the ammonia is separated using metal halide sorbents. The ammonia is subsequently desorbed and stored in liquid phase using refrigerated tanks operating at ~33 °C at close to atmospheric pressures (1.1–1.2 bar). When there is a shortage of wind energy, the ammonia stored is fed to solid oxide fuel cells where it is converted into nitrogen, water, and electricity. For this, no additional ammonia cracking is required, as NH₃ will be able to dissociate over the Ni-based electrocatalyst in the solid oxide fuel cells [51].

In this energy storage system, the battolysers will deliver power to cope with short-term energy generation fluctuations, whereas the ammonia will deliver power to manage the seasonal energy generation fluctuations.

3.1. Demineralized water production

For the production of hydrogen, pure water is required. In small island developing states, clean water is obtained from seawater. Due to environmental considerations related to the release of large quantities of brine in coastal regions, it was decided to employ a technology with a low brine footprint. Zero liquid discharge (ZLD) is a technique that combines the production of pure water as well as a highly concentrated brine, together with evaporation of the water from the salt in the final brine solution, avoiding the release of brine to the environment. For ZLD, reverse osmosis can be used to produce purified water from seawater upon using a combination of low rejection reverse osmosis (LRRO) with high rejection reverse osmosis (HRRO) to overcome osmotic pressure limitations at high brine concentrations [52] (see Section 2 of SI). The specific energy consumption of this HRRO/LRRO process to produce brine streams of ≥4 Molar is ca. 5.1 kWh/m³, which is substantially lower than conventional ZLD systems [52]. Since mechanical vapor compression (MVC) systems offer higher energy efficiencies than other evaporative technologies, it was decided to use the former to separate the salts from the brine solutions [53]. For conventional RO, high rejection membranes can be used. Notably, both technologies require less than 1% of the total energy consumption for ammonia production, and the choice of the technology will not significantly affect the cost of the total system (see Section 2 of the SI). Thus, the ZLD technology is preferred because it has a lower environmental footprint in terms of brine discharge [54].
3.2. Ammonia production

Hydrogen is produced by electrolysis using a battolyser, and nitrogen is purified from air using pressure swing adsorption. For the ammonia synthesis process, there are three main options to consider that have technology readiness levels relevant for practical implementation, including: high-pressure Haber-Bosch, medium-pressure Haber-Bosch, and absorbent enhanced Haber-Bosch. The advantages and disadvantages are summarized in Table 2.

For a relatively small-scale process, it is beneficial to work at moderate process conditions. This means that lower temperatures and lower pressures are preferred. High pressure Haber-Bosch works at around 400–550 °C and 300–460 bar [8] and requires a high CapEx, medium pressure Haber-Bosch works at conditions of 350–525 °C and 100–200 bar [27]. Notably, absorption enhanced Haber-Bosch uses more moderate temperatures of 370–400 °C and pressures of usually 10–30 bar [55,56], rendering the latter alternative with the lowest costs at smaller scales [32]. The absorption enhanced Haber-Bosch process is shown in Fig. 4.

There are multiple options for the ammonia synthesis catalyst. While conventional processes use iron catalysts [57], ruthenium catalyst allow for operation at milder conditions due to their higher catalytic activity [37]. This allows for better intermittent operation, as the synthesis loop can be operated at moderate conditions. As a result, it was decided to opt for a relatively small-scale process, which is beneficial to work at moderate process conditions. This means that lower temperatures and lower pressures are preferred. High pressure Haber-Bosch works at around 400–550 °C and 300–460 bar [8] and requires a high CapEx, medium pressure Haber-Bosch works at conditions of 350–525 °C and 100–200 bar [27]. Notably, absorption enhanced Haber-Bosch uses more moderate temperatures of 370–400 °C and pressures of usually 10–30 bar [55,56], rendering the latter alternative with the lowest costs at smaller scales [32]. The absorption enhanced Haber-Bosch process is shown in Fig. 4. Further explanations for all process decisions and choice of catalyst can be found in sections 3-9 of the SI.

There are multiple options for the ammonia synthesis catalyst. While conventional processes use iron catalysts [57], ruthenium catalyst allow for operation at milder conditions due to their higher catalytic activity [37]. This allows for better intermittent operation, as the synthesis loop can be operated at moderate conditions. As a result, it was decided to opt

### Table 2
Possible ammonia synthesis options, modified from Ref. [8].

| Processes                | Advantages                                           | Disadvantages                                      |
|--------------------------|------------------------------------------------------|----------------------------------------------------|
| High pressure Haber-Bosch | Well known, no sharp separation required.             | High pressure, temperature and capital expenditure (CapEx). |
| Medium pressure Haber-Bosch | Well known, no sharp separation required.           | Large scale, refrigeration required.               |
| Absorption enhanced Haber-Bosch | Low pressure, low temperature, no large scale required. | Efficient separation required.                     |

**Fig. 4.** Process design for absorption enhanced Haber-Bosch, modified from Ref. [32].

**Fig. 5.** Monthly energy consumption and production corrected for short-term and seasonal efficiency losses using the small-scale ammonia synthesis process based on AEHB coupled with battolyzers for the island of Curaçao.
for a Ru/Ba-Ca(NH₃)₂ catalyst (see section 6 of the SI). One aspect to keep in mind is that ruthenium extraction is a CO₂ intensive process, which results in a carbon footprint increase of ca. 0.01 kg of CO₂/kg NH₃ (section 8 in the SI). For this reason, the carbon penalties as well as the overall processes costs associated to the selection of the catalyst were taken into consideration when choosing between iron and ruthenium.

For the selection of the sorbent for ammonia absorption, alkaline chloride and bromides, either supported on silica or zeolite Y are the most promising options. Alkali metal chlorides and bromides absorb similar amounts of ammonia on a mass-to-mass basis, but chlorides are preferred because of their lower costs and higher stability [58]. Here, it was found that 40 wt% CaCl₂ on SiO₂ is the most suitable option for the absorption (section 7 of the SI).

### 3.3. Ammonia storage

For the storage of ammonia, there are several options. Here, three storage options are considered, including: non-refrigerated storage, semi-refrigerated storage, and low-temperature storage (Table 3). In order to ensure sufficient capacity to fit one year of seasonal energy storage including a 20% safety margin, low-temperature ammonia storage is the preferred alternative. This option also stores the largest amount of ammonia per ton of building steel.

### 3.4. Ammonia-to-Power

The final step in the power-to-ammonia-to-power step is the conversion of ammonia to energy. Two options for energy generation are the conversion of ammonia to hydrogen to power, or the direct use of ammonia. Aziz et al. recommended the direct use of ammonia [59]. Patel and Farooque [60] illustrate that for a process of approximately this scale, direct fuel cells and fuel cells with thermal energy recovery systems (heat to electricity) are the most feasible options for electricity generation. The most preferred direct fuel cell is the Solid Oxide Fuel Cell (SOFC) [59]. Here, anion conducting solid oxide fuel cells (SOFC-O), proton conducting solid oxide fuel cells (SOFC-H), and a combination of solid oxide fuel cells and gas turbines (SOFC-GT) have been considered. The SOFC-GT system was discarded as the increase the CapEx and OpEx associated to the turbines and compressors did not justify the electrical efficiency gains of ca. 2% [61]. This is due to the inefficient conversion of waste heat to electricity in solid oxide fuel cells. The final selection of the equipment was SOFC-H, instead of SOFC-O, as the former can operate under milder conditions while achieving a similar efficiency of ca. 55 %LHV [8]. Sufficient SOFC-H capacity was considered in the design to handle the peak demand. That is when no direct wind energy or battriler energy storage is available. Peak demand for Curaçao is estimated to be 164 MW, based upon consumption [50], corrected for energy consumption increases in recent years [62]. Synergy between N₂ production, NH₃ production, and NH₃ power generation has been assessed by Aziz et al. [63], resulting in a reduced energy consumption of N₂ production. Furthermore, it provides an oxygen-rich flow from the N₂ production, as well as a purge flow from ammonia synthesis, that can both work as useful feed in ammonia power generation units. This synergy is, however, not utilized in this model, as ammonia decomposition generates thermal energy during electricity shortages, whereas nitrogen and ammonia are generated during electricity excesses.

### Table 3

| Type                      | Typical pressure, bar | Design temperature, °C | t ammonia /t steel | Capacity, ton ammonia | Refrigeration compressor               |
|---------------------------|-----------------------|------------------------|-------------------|-----------------------|----------------------------------------|
| Pressure storage          |                        |                        | 2.8               | <270                  | None                                   |
| Semi refrigerated storage | –                     | Ca. 0                  | 10                | 450–2,700             | Single stage                           |
| Low temperature storage   | 1.1–1.2               | –33                    | 41–45             | 4,500–45,000          | Two stage                              |

### 3.5. Energy efficiency of P2A2P

The energy consumption of the entire power-to-ammonia process is listed in Table 4. Notably, electrolysis is responsible for the majority of the energy consumption, with 8.7 kWh kg-NH₃⁻¹, followed by the ammonia synthesis loop.

In this contribution, no energy recovery in the absorbers is assumed. Thus, absorbers will utilize 4.2 kWh/kg NH₃. Including heat integration could decrease this number at the expense of increasing the capital expenditures. Furthermore, this value assumes that all absorption beds are cooled and heated at a constant two cycles per hour, lower energy consumptions are possible if the amount of absorption beds working is scaled in relation to the ammonia production size at a certain moment. The remainder of the ammonia synthesis loop energy consumption is due to compressor duty. The total energy consumption is 13.9 kWh/kg NH₃. While these values are in the range of large scale ammonia synthesis from natural gas, coal, and fuel oil with consumptions of 7.8, 10.6, and 11.7 kWh/kg ammonia, respectively [64], it is clear that the energy consumption can be significantly improved.

### 3.5.1. Carbon footprint of P2A2P

In literature, Life Cycle Analyses of renewable powered ammonia processes are widely reported and often range between 0.3 and 0.58 kg CO₂/kg NH₃ for ammonia processes using windmills [42] – [44]. Here, we estimate that this process generates ca. 0.45 kg CO₂/kg NH₃. Converting the produced ammonia into electricity using SOFCs with 0.32 kg NH₃/kWh leads to a carbon footprint of 0.158 kg CO₂/kWh for the P2A system (See section 8 of the SI). The carbon footprint of materials and construction for SOFC systems is estimated to be 0.114 kg CO₂ per kWh of generated energy over its lifetime, including stack replacements [41]. The total carbon footprint of P2A2P is assumed to be 0.272 kg CO₂/kWh. Direct wind power averages a carbon footprint of 0.019 kg CO₂/kWh [45]. The carbon footprint of direct wind power and P2A2P storage combined, averages to ca. 0.03 kg CO₂/kWh, see figure S5 in the SI.

### 4. Economic evaluation

The levelized costs were evaluated using the equipment size required for the process. For this purpose, energy production and consumption profiles for Curaçao are made to calculate the required storage capacity. The storage capacity is then correlated to ammonia production volumes and equipment sizes to find the levelized costs of electricity. The detailed description can be found in Sections 9 and 10 of the SI.
4.2 Wind farm and process capacity

The model shows that a wind farm with a capacity of 219 MW is required to cover the energy consumption of Curaçao and storage energy losses. The energy generation fluctuations are covered using balltysers for short-term energy storage and using ammonia for seasonal storage. To cover the seasonal fluctutations, the process produces 1891 kg-NH$_3$ h$^{-1}$ on average. The required maximum capacity of the plant is calculated to be 4612 kg-NH$_3$ h$^{-1}$, leading to a net capacity factor of 41% (see Section 1 of the SI).

4.4 Levelized cost of electricity and payback period

To estimate the levelized cost of electricity (LCOE), it was assumed that the Operational Expenditures (OpEx) were constant throughout the project lifetime with an exception for windmill maintenance after 10 and 15 years. It was calculated that the LCOE for the herein proposed process is ca. 0.13 USD/kWh (20 years lifetime at a 5% annual discount...
Payback periods of ca. 20, 10.8, and 6.6 years were calculated for generation revenues of 0.125 USD/kWh, 0.20 USD/kWh and 0.30 USD/kWh, respectively, at a 5% discount rate. LCOEs of 0.09, 0.13, and 0.17 USD/kWh were estimated for discount rates of 0, 5, and 10%, respectively (see section 10 in the SI). To determine the economic feasibility of the combined wind energy and ammonia energy storage system, a comparison was made with conventional fossil fuels (heavy fuel oil, natural gas, and coal), with and without carbon capture and storage (CCS). A summary of the CapEx and OpEx (except feedstock cost) for energy production from fossil fuels is listed in Table 6.

All the technologies utilized a discount rate of 5% to ensure a fair comparison. Furthermore, constant O&M costs throughout the years and no end-of-life value were assumed in the final cost estimations. The coal price was estimated in the range of 42.7–96.5 USD ton⁻¹, based on shipping tariffs from Puerto Bolivar to Curaçao [68] and current spot prices [69]. For the natural gas power plant, LNG (liquefied natural gas) spot prices are taken at 8–13 USD MMBtu⁻¹ (8.44–13.72 USD Gj⁻¹) based upon current trends [70]. Heavy fuel prices are ranging between 0.106 and 0.130 USD/kWh based upon ranges within equivalent systems in countries [66] with similar energy prices [71].

The cost of Carbon Capture and Storage (CCS) was also estimated for natural gas-based and coal-based energy production, based upon 90% CCS [72]. The LCOEs for the combined wind energy and ammonia energy storage system (P2A2P), as well as fossil-based energy production with or without CCS are shown in Fig. 7.

As shown in Fig. 7, the combined wind energy and ammonia energy storage system is economically competitive with the fossil-based energy production alternatives, even in absence of CCS. When CCS is included, the combined direct-wind energy and P2A2P storage system becomes the most cost competitive option on average. Here, it should be noted that no natural CO₂ storage facilities, such as salt mines or exhausted natural gas reservoirs, exist near Curaçao. Thus, one can envision that the total cost of CCS can be significantly higher than the average costs used in the current analysis.

The CO₂ emission data from fossil fuels in Table 6 was used to calculate the carbon footprint of the different alternatives. A comparison of CO₂ footprints is shown in Fig. 7. Combined direct-wind energy and P2A2P energy storage system has the lowest carbon footprint, even when CCS is applied for natural gas or coal. Here, it is important to mention that the LCOE values shown in Fig. 7 do not consider potential carbon taxes. However, the emission of CO₂ is already penalized in some countries. In the EU, the current carbon price is above 50 USD t-CO₂⁻¹ [73]. The costs of electricity production in Fig. 7 are compared with- and without a carbon tax of 50 USD t-CO₂⁻¹ in Fig. 8. Notably, in the scenario with 50 USD t-CO₂⁻¹, coal and heavy fuel-based electricity generation is not competitive. Only the combined direct-wind energy and P2A2P storage system, and natural gas-based electricity generation without CCS are cost competitive options.

5. Conclusion

The estimated LCOE for the process using P2A2P was 0.13 USD/kWh at a discount rate of 5% using SOFC-Hs for the island of Curaçao. This resulted in an LCOE lower than heavy fuel and coal-based energy with rate).
90% Carbon Capture, and an LCOE on par with natural gas-based energy without Carbon Capture, and coal-based energy without Carbon Capture. Despite the implementation of two stroke ammonia engines as alternative to SOFC-Hs is expected to be more likely to occur in the short term, due to the easier installation and operation of these units, it is expected that this will increase the LCOE of P2A2P by a marginal 5–10%. These results suggest that the P2A2P process is economically feasible for Curaçao with a RTE of the long-term storage process using ammonia of around 20.5%. Here, the bottlenecks are the energy losses in the electrolyzers, the SOFC-Hs, and the absorption columns. The CO₂-footprint of the combined wind energy and ammonia energy storage system is 0.03 kg/kWh, which is significantly lower than the carbon footprint of current fossil-based energy generation technologies. This makes green ammonia energy storage an interesting alternative for Curaçao. Extrapolating these results to other SIDS will be strongly related to the availability of wind and sun energy, seasonal generation patterns, land availability, and annual consumption profiles. Nevertheless, these results indicate that even in a small island like Curaçao, green ammonia can be employed to support the energy transition.

Credit author statement

Victor Sagel: Development of the modelling methodology, validation, investigation, data processing, and writing of the original draft. Kevin H.R. Rouwenhorst: Formal analysis, writing review and editing, and visualization. Jimmy Faria Albanese: Conceptualization of the project, visualization, supervision, project administration, formal analysis, editing and reviewing of the manuscript, and funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jimmy A. Faria A. reports financial support was provided by Nederlandse Organisatie voor Wetenschappelijk Onderzoek Utrecht.

Acknowledgements

The research project was funded by the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO) Project Number NWOC.A.2019.027 called RESILIENT-ISLAND.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112381.

References

[1] Ormes S. How does climate change influence extreme weather? Impact attribution research seeks answers. Proc Natl Acad Sci U S A 2018;115:8232–5. https://doi.org/10.1073/pnas.1813931115.
[2] Shirley R, Kammen D. Renewable energy sector development in the Caribbean: current trends and lessons from history. Energy Pol 2013;57:244–56. https://doi.org/10.1016/j.enpol.2013.01.049.
[3] U.S. Department of Energy. Energy snapshot bonaire. 2015. p. 1–4. https://www.oost.org/biblio/1647709-energy-snapshot-bonaire. [Accessed 11 July 2021].
[4] U.S. Department of Energy. Energy snapshot Aruba. 2015. p. 1–4. https://www.oost.org/biblio/1647715-energy-snapshot-aruba. [Accessed 11 July 2021].
[5] U.S. Department of Energy. Energy snapshot curacao, 4; 2015. https://www.oost.org/biblio/1647713-energy-snapshot-curacao. [Accessed 11 July 2021].
[6] U.S. Energy Information Administration. Electric Power Monthly. 2015. p. 1.
[7] Rouwenhorst KHR, Van der Ham AGJ, Mul G, Kersten SRA. Islanded ammonia power systems: technology review & conceptual process design. Renew Sustain Energy Rev 2016;114. https://doi.org/10.1016/j.rser.2015.10.039.
[8] Daw J, Stout S. Building island resilience through the energy , water , food nexus building island resilience through the energy , water , food nexus. 2019. p. 1–15. July 11, 2021, https://www.oost.org/biblio/1569216-building-island-resilience-through-energy-water-food-nexus.
[38] Nakao T, Tada T, Hosono H. First-principles and microkinetic study on the mechanism for ammonia synthesis using Ru-loaded hydride catalyst. J Phys Chem C 2020;124. https://doi.org/10.1021/acs.jpcc.9b10550. 2070-8.

[39] Inoue Y, Kitano M, Kishida K, Abe H, Niwa Y, Sasaee M, et al. Efficient and stable Ammonia synthesis by self-organized flat Ru nanoparticles on calcium amide. ACS Catal 2016;6:7577–84. https://doi.org/10.1021/acscatal.6b01940.

[40] Rouwenhorst KFR, Van der Ham AGJ, Jefferts I. Beyond Haber-Bosch: the renaissance of the Claude process. Int. J. Hydrog. Energy 2021;46(41):21566–79. https://doi.org/10.1016/j.ijhydene.2021.04.014.

[41] Staffell I, Ingram A, Kendall K. Energy and carbon payback times for solid oxide fuel cell based domestic CHP. Int J Hydrogen Energy 2012;37:2509–23. https://doi.org/10.1016/j.ijhydene.2011.10.060.

[42] Liu X, Elgowainy A, Wang M. Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products. Green Chem 2020;22:5751–61. https://doi.org/10.1039/d0gc00201a.

[43] Bicer Y, Dincer I, Zamfirescu C, Vezina G, Raso F. Key Life Cycle Assessment Numbers for NH3, Green and Brown Energy. 2016. https://www.ammoniaenergy.org/paper/key-life-cycle-assessment-numbers-for-nh3-green-and-brown-energy/. [Accessed 15 May 2021].

[44] Al-Breiki M, Bicer Y. Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization. J Clean Prod 2021;279:123481. https://doi.org/10.1016/j.jclepro.2020.123481.

[45] Arvesen A, Hertvig EG. Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs n.d. https://doi.org/10.1016/j.jser.2012.06.023.

[46] Rogers T, Ashpine M, Koon Koon R, Atherley-Ikechi M. Onshore wind energy carriers including production, storage, overseas transport and utilization. J Clean Prod 2020;227:123481. https://doi.org/10.1016/j.jclepro.2020.123481.

[47] Nakao T, Tada T, Hosono H. First-principles and microkinetic study on the mechanism for ammonia synthesis using Ru-loaded hydride catalyst. J Phys Chem C 2020;124. https://doi.org/10.1021/acs.jpcc.9b10550. 2070-8.

[48] Johnson NH, Solomon BD. A net-present value analysis for a wind turbine purchase at a small US college. Energies 2010;3:943–59. https://doi.org/10.3390/en3050943.

[49] Worlddata. Energy consumption in Curacao n.d. https://www.worlddata.info/ame/curacao/energy-consumption.php. [Accessed 12 October 2020].

[50] Yash Agarwala. 100 % renewable energy transition in small island developing states (SIDS). 2017. p. 129. http://resolver.tudelft.nl/uuid:a0bc6111-618f-490f-94aa-87f9508a8bd6.

[51] Ember. Carbon price viewer - ember n.d. https://ember-climate.org/data/carbon-price-viewer/. [Accessed 2 July 2021].