Supporting Online Material

Renewable electricity generation in small island developing states: the effect of importing ammonia

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Index

Supplementary Material S1

The AE-HB process was modeled using Aspen Plus, as shown in **Figure S1**. As compared to the model used in reference [1], energy optimization has been performed in the absorption beds. The absorption beds are now modelled to obtain an average cycle time of 30 minutes depending on feed flow, as compared to a constant cycle time of 30 minutes, regardless of feed flow. The absorption beds were modeled as fictive separation columns ('Sep2' columns, B3 in **Figure S1**), in combination with a cooler and pressure valve to maintain accurate temperatures and pressures. The energy consumption of the absorption columns was calculated in Matlab. Furthermore, higher cooling water flows were taken to limit the increase in temperature to 10 ^{o}C in all cooling water outflows, to reduce the impact on marine life. A purge fraction of 0.5% was found to be suitable in this process.

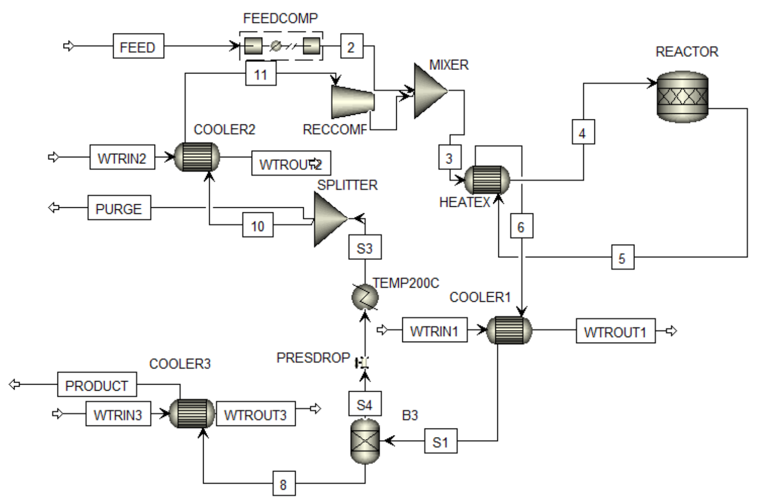

Figure S1: AE-HB process ASPEN model as utilised in this manuscript.

Supplementary Material S2

The data from Aspen Plus in combination with the data from Matlab were linked towards a Matlab script, in which an iterative loop was present to later calculate the required equipment sizes to perform P2A2P.

The inputs of the second part of the model are: average energy demand, peak demand, lowest assumed demand, average seasonal demand patterns, average daily demand patterns, average seasonal wind patterns, average daily wind patterns, short-term storage round-trip efficiency (RTE), and wind-to-power wind turbine correlations. Using the demand patterns, it is possible to estimate how the energy demand will fluctuate throughout a day, and throughout the year. Using wind patterns and wind-to-power wind turbine correlations, it is possible to estimate the average daily and seasonal energy generation pattern of a wind turbine. With the demand patterns, in combination with the wind patterns, the known RTE of battolysers, and the calculated RTE of P2A2P, it was possible to quantify the size of the wind turbine, production loop, and storage systems required. For Curaçao, demand patterns were utilised as described in reference [2]. Peak demand is estimated at 143 MW, taken as the highest energy consumption in a day, in the month with the highest energy consumption. The minimum demand is calculated with the same strategy to be 76 MW. For Fiji, real-scenario demand curves from reference [3] are used, leading to estimates of peak demand and minimum demand of 165 MW and 60 MW, respectively.

The model has been run for the cases of Curaçao and the island Viti Levu on Fiji, with geographical coordinates of -68.95 W, 12.15 N, and -17.6 N, 176.75 W, respectively, at 100 m hub height. ERA5 data have been utilised to obtain wind patterns from 2007–2020 in the form of averaged wind speeds per hour per month [4]. To correlate wind speed to energy output, a wind turbine was modelled that would be suitable in Viti Levu and Curaçao. The main considerations were the expected net capacity, hub height, and wind turbine size. The selected wind turbine was the Vestas P82 1.65 MW [5], with the model utilising a polynomial fit over datapoints as presented in reference [6]. The data in Figure 3a and 9a were calculated by calculating the daily excess energy pattern when comparing a daily generation curve to the average daily demand. Subsequently, an excess pattern was calculated from comparing the daily demand pattern to the average daily generation. The two resulting curves were then combined to combine daily supply and demand patterns. It should be mentioned that this technique is an approximation method, as more accurate calculation methods significantly complexify the model, leading to processing times of several orders of magnitudes higher. The total losses in the battolysers are a small fraction of the total energy streams; thus, the influence of the approximation method is small on the overall system.

Supplementary Material S3

Green ammonia production is currently estimated to cost in excess of 700 USD/t NH_3 [7, 8]. However, production costs are expected to decrease to below 500 USD/t NH_3 for the most optimal locations by 2030 [7–12]. Further cost reductions result in a cost below 350 USD/t NH_3 by 2050 [7, 10]. Transportation via ship typically costs 30–100 USD/t ammonia, depending on the distance and fuel cost [13]. The base case ammonia cost at location, e.g., Curaçao or Fiji, was assumed to be 500 USD/t NH_3. As an alternative to green ammonia, low-carbon fossil-based ammonia with carbon capture and storage (CCS) can be utilised, which is expected to have a market value of 350-400 USD/t ammonia [14].

Supplementary Material S4

The ammonia flows as shown in Figure 5 and 10 and was used to calculate the levelized costs of electricity. The storage tank sizes are illustrated as well. For the scaling of the storage tanks, two boundary conditions will be in place, scenario 1 at 0% import; 1.2 times annual production at an average capacity of 50% is assumed. Scenario 2 at 100% import, the storage tanks are sized to contain 1 month of ammonia supply for the month with the largest energy shortage. The storage tank estimations for the scenario of combined import and on-site production is estimated using the equation: $Storage\ tank\ size\ scenario\ 3 = tank\ size\ scenario\ 1 + importfraction * tank\ size\ scenario\ 2$

The storage tank size of scenario 1 is automatically corrected for the import fraction in the script at the respective wind farm size, and does therefore not need an import fraction parameter in the equation.

Supplementary Material S5

Energy generation, energy utilisation goals, and supply/demand patterns are given for the cases of 0–100% import. From these figures, it is illustrated that significantly less energy is going towards P2A2P at higher import percentages. However, it also shows that the excess in energy increases at higher import percentages. The generation and demand curves for Curaçao and Viti Levu, respectively, are shown in **Figure S2** and **Figure S3**.

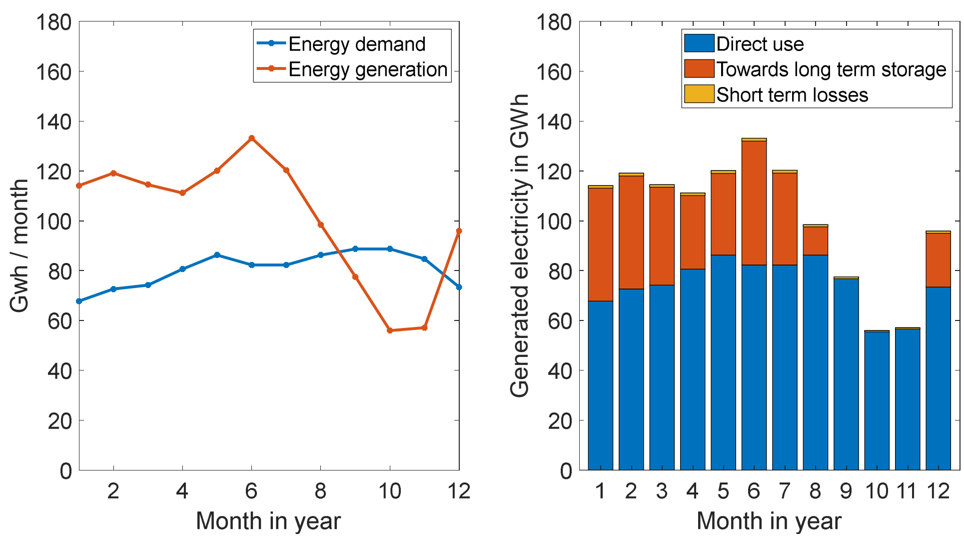

Figure S2 a (left) b (right): Energy generation and utilisation patterns at 0% import, Curaçao.

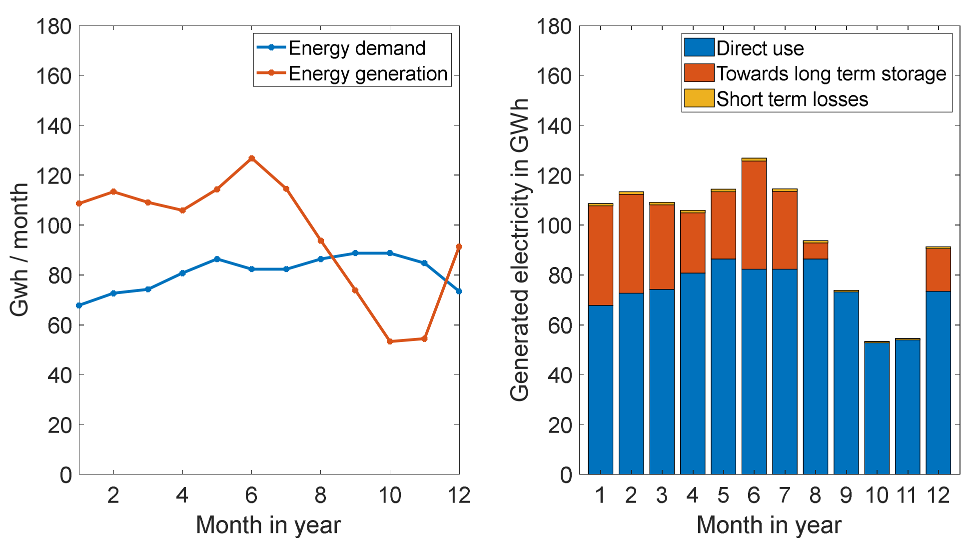

Figure S2 c (left) d (right): Energy generation and utilisation patterns at 25% import, Curaçao.

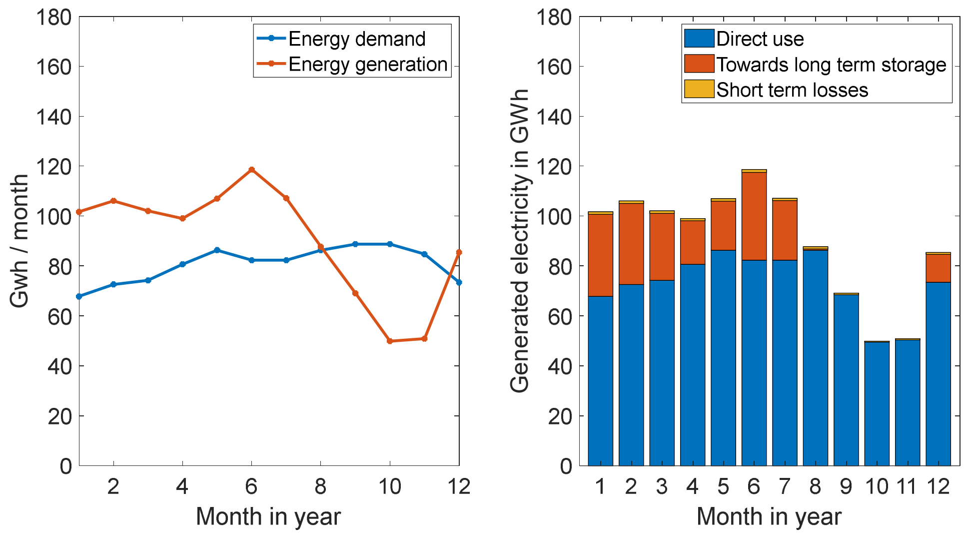

Figure S2 e (left) f (right): Energy generation and utilisation patterns at 50% import, Curaçao.

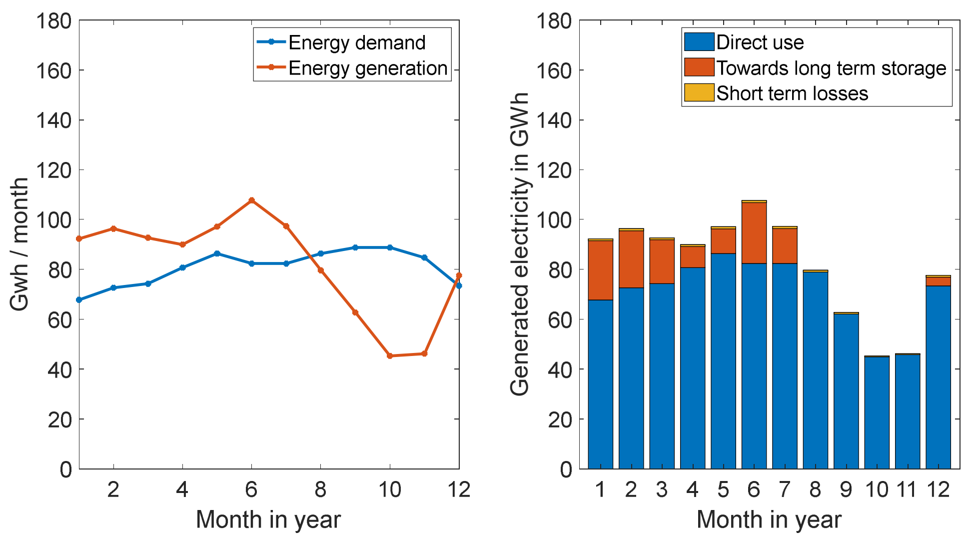

Figure S2 g (left) h (right): Energy generation and utilisation patterns at 75% import, Curaçao.

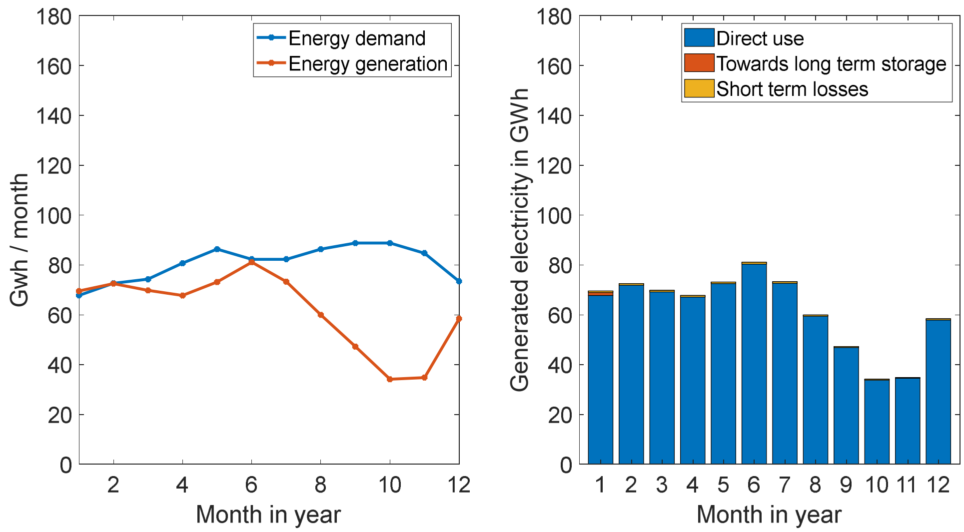

Figure S2 i (left) j (right): Energy generation and utilisation patterns at 100% import, Curaçao.

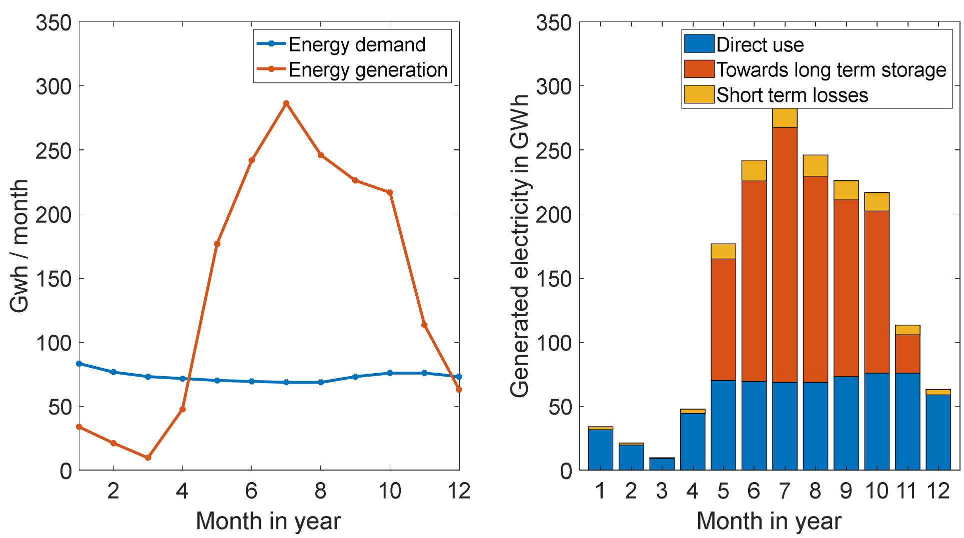

Figure S3 a (left) b (right): Energy generation and utilisation patterns at 0% import, Viti Levu.

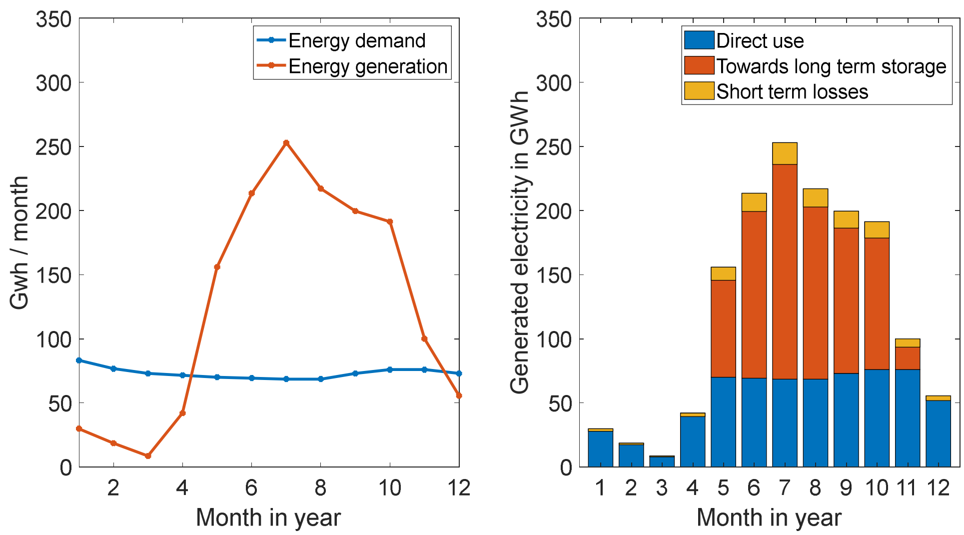

Figure S3 c (left) d (right): Energy generation and utilisation patterns at 25% import, Viti Levu.

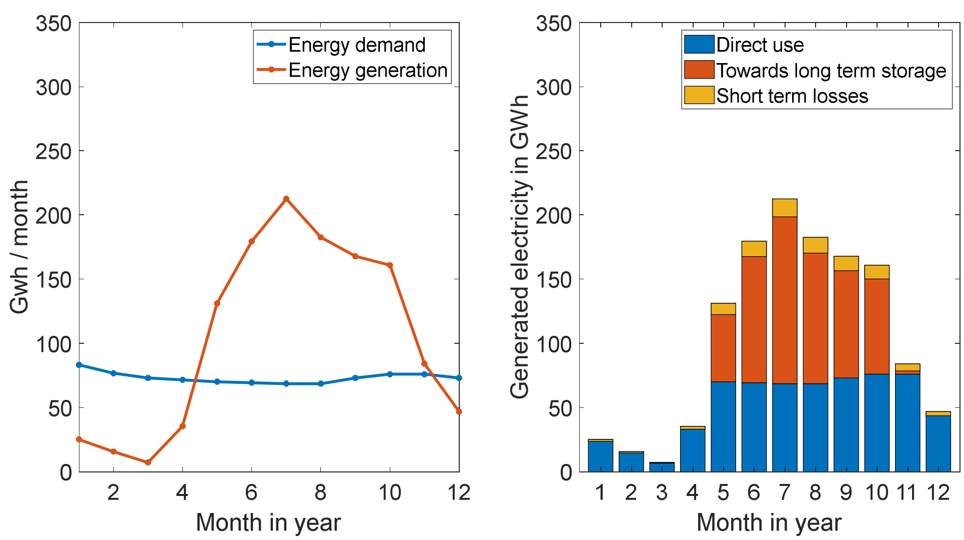

Figure S3 e (left) f (right): Energy generation and utilisation patterns at 50% import, Viti Levu.

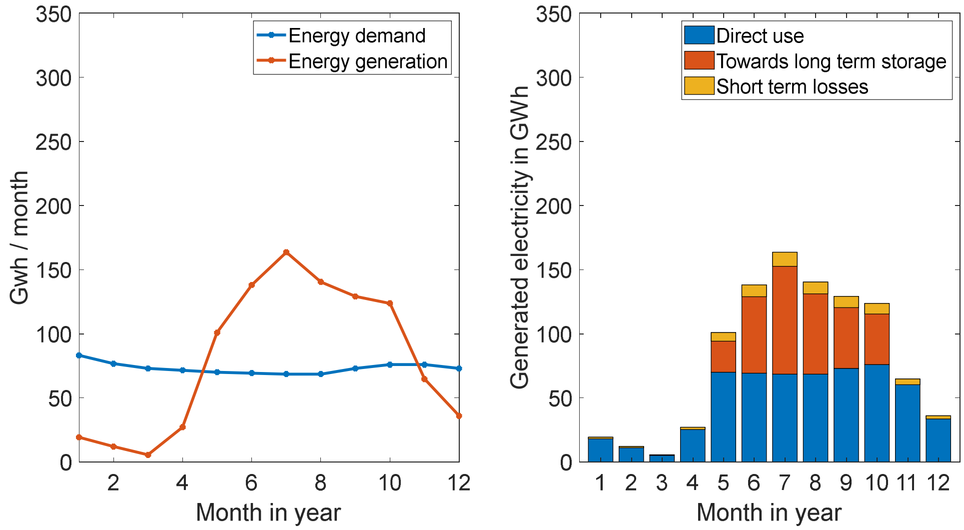

Figure S3 g (left) h (right): Energy generation and utilisation patterns at 75% import, Viti Levu.

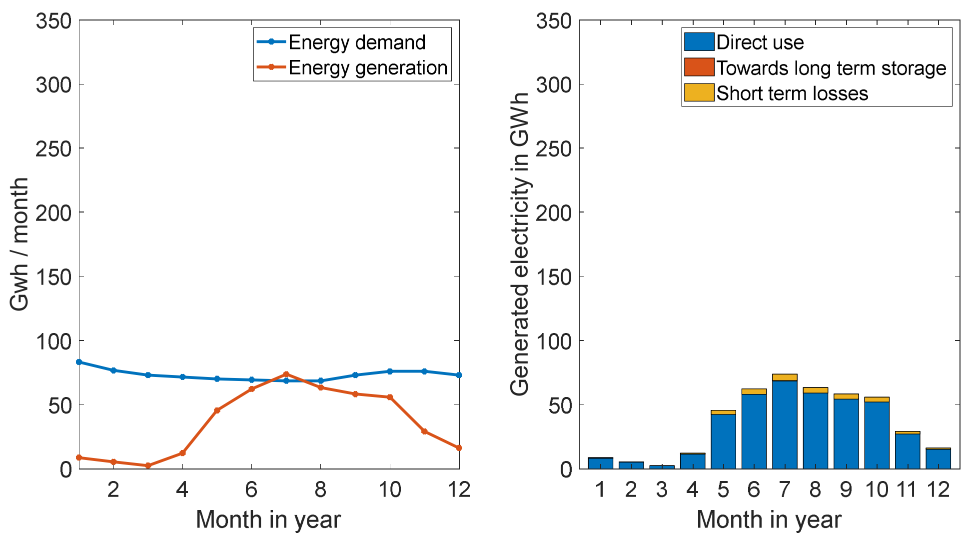

Figure S3 i (left) j (right): Energy generation and utilisation patterns at 100% import, Viti Levu.

Supplementary Material S6

For Curaçao, data from ultra-supercritical coal decomposition, either with or without CCS, were used to estimate the costs of coal alternatives, from reference [15]. For LNG, 'Combined-Cycle 1x1x1, Single Shaft' data, with or without CCS being used, from reference [15]. Data from the heavy fuel alternative are gathered from reference [16]. For all technologies, a discount rate of 5% annually was used. Constant O&M costs, and no scrap value is assumed. The prices of coal, natural gas, and heavy fuel are estimated to be 42.7-96.5 USD ton^{-1}, 8-13 USD $MMBTU^{-1}$, and 0.106–0.130 USD kWh^{-1}, based upon the estimations performed in our previous work [1]. Further data about the costs breakdown of the alternatives is shown in Table S1.

Table S1. Data about coal-, and gas combined-cycle plants, with and without carbon capture and storage (CCS), data from reference [15], heavy fuel CapEx, and O&M from [16], energetic values per mass from [17].

	CapEx (USD/kW)	Fixed O&M (USD/kW-y)	Variable O&M (USD/MWh)	Net nominal heating rate (kWh/kWh)
Coal without CCS	3676	40.58	4.50	2.53
Coal with CCS	5876	59.54	10.98	3.67
Natural gas without CCS	1084	12.20	2.55	1.89
Natural gas with CCS	2481	27.6	5.84	2.09
Heavy fuel oil without CCS	2162	N/A	16.9	2.35

Supplementary Material S7

For Fiji, the most relevant imported fuels are LPG (liquefied petroleum gas) [18] and DFO (diesel fuel oil) [19]. LNG [18] and coal [20] are not used on Fiji in any significant form. To estimate the costs of the alternatives, data from 'Internal Combustion Engines' were used for the diesel option, and data from 'Combined-Cycle 1x1x1, Single Shaft', either with or without CCS, were used for the LPG alternatives.

For diesel, prices have ranged between 1.97–2.31 Fiji Dollar/Liter in the second half of 2021 [42, 44, 45], whereas LPG prices have ranged between 2.47–3.42 Fiji Dollar/kg. Based upon a currency exchange rate of 0.47 Fiji Dollar to 1 Fiji Dollar [23], and the fact that fossil fuel prices have been historically high in the second half of 2021, a range of 0.8–1.2 USD/Liter was assumed to be realistic for diesel, and 1–1.7 USD/kg for LPG. The composition of LPG is not known for Fiji, thus an equal composition on mass basis of propane and butane was assumed.

Table S2. Data about LPG combined-cycle plants, with and without carbon capture and storage (CCS), and simple diesel internal combustion engines, data from [15], energetic values per mass from [17].

	CapEx (USD/kW)	Fixed O&M (USD/kW-y)	Variable O&M (USD/MWh)	Net nominal heating rate (kWh/kWh)
LPG without CCS	1084	12.20	2.55	1.89
LPG with CCS	2481	27.6	5.84	2.09
Simple diesel without CCS	1810	35.16	5.69	2.43

Supplementary Material S8

Effect of wind farm cost

It was illustrated in the main manuscript that at different ammonia prices, the optimum scenario regarding local production or import may vary. In this study, relatively high costs for CapEx, OpEx, and maintenance were assumed. These costs were based on the results from a shareholder meeting for wind turbines on Barbados [24]. The source has stated that the quality of infrastructure has a large influence on the total costs of the realization of a wind farm, and that Barbados has poor infrastructure [24]. The cost estimates of the wind farm on Curaçao and Viti Levu was based upon the estimate on Barbados, and is deemed conservative based upon the quality of infrastructure of Barbados versus Curaçao and Viti Levu.

As prices might be different in reality for Curaçao and Viti Levu, a sensitivity analysis was performed to find the influence of wind farm costs on the cheapest option of operating an energy grid, as shown in Figure S13 and S14 with more optimistic cases. Here, three scenarios can be identified at CapEx rates of 2366 USD/kW, 2000 USD/kW, and 1500 USD/kW, with linearly scaling OpEx and maintenance costs. The base scenario (1) assumes 2366 USD/kW CapEx, 64.55 USD/kW/year OpEx, 413 USD/kW maintenance year 10, 304 USD/kW maintenance year 15, based upon estimates as shown in reference [24]. Scenario (2) assumes 2000 USD/kW CapEx, 54.56 USD/kW/year OpEx, 349 USD/kW maintenance year 10, and 256.97 USD/kW maintenance year 15. Scenario (3) assumes 1500 USD/kW CapEx, 40.93 USD/kW/year CapEx, 261.83 USD/kW maintenance year 10, and 192.73 USD/kW maintenance year 15. The results for Curaçao and Viti Levu are illustrated in Figure S13 and S14, respectively. In Figure

S13, the results illustrate for Curaçao that depending on the assumed costs of green ammonia and wind turbines, either the configuration with on-site ammonia production, or full imported green ammonia, will be the cheapest option. When importing all ammonia, the LCOE is found to be 0.09–0.14 USD/kWh, depending on the costs of green ammonia and wind turbines assumed in the model.

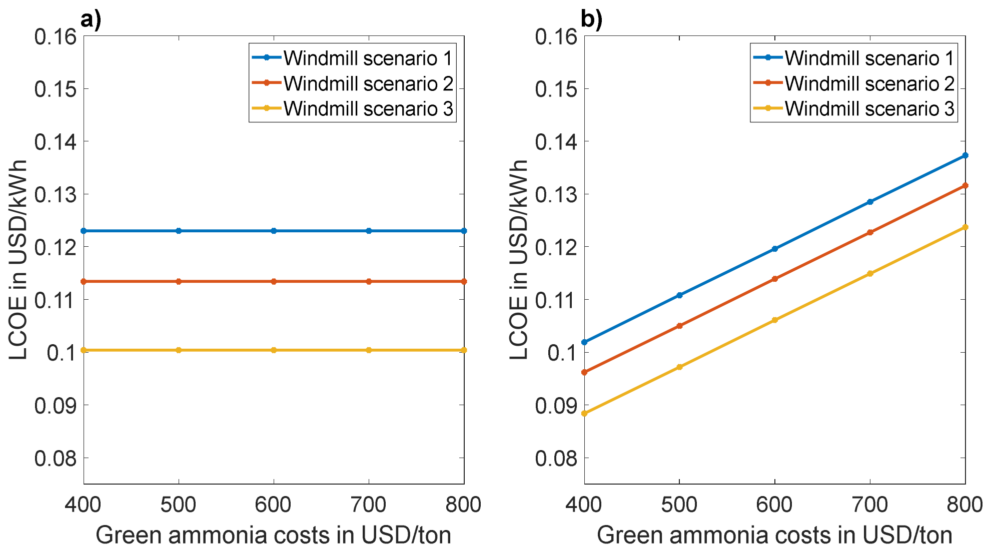

Figure S13. LCOE in USD/kWh versus ammonia import costs a) without green ammonia import, b) with full green ammonia import, at different wind farm costs for Curaçao.

In Figure S14, it is clear that importing green ammonia is the cheapest option for all assumed green ammonia and wind turbines costs configurations for Viti Levu. When importing all ammonia, the LCOE is found to be 0.26–0.42 USD/kWh, depending on the costs of green ammonia and wind turbines.

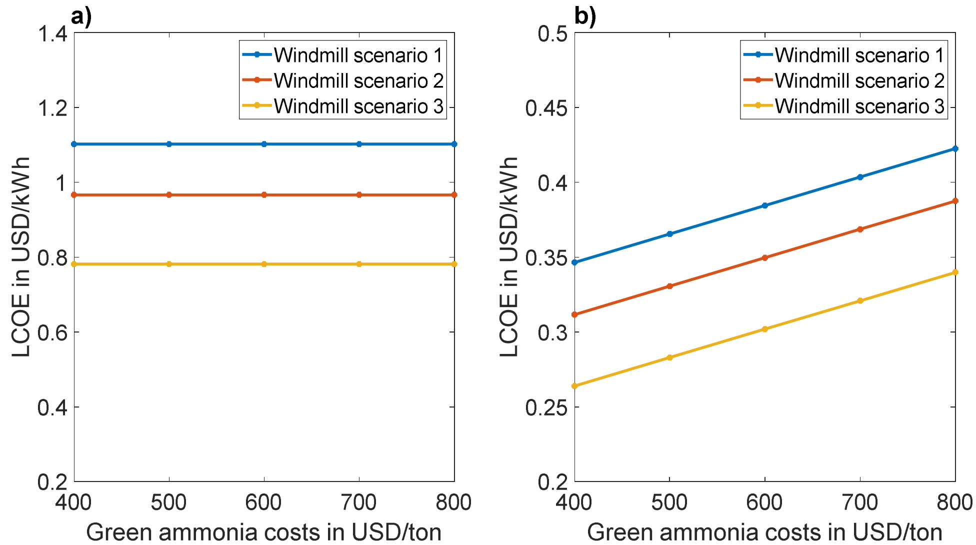

Figure S14. LCOE in USD/kWh versus ammonia import costs a) without green ammonia import, b) with full green ammonia import, at different wind farm costs for Viti Levu.

Supplementary Material S9

Effect of SOEC lifetime

In addition to the wind farm, the fuel cells are a large driver of the costs. The lifetime of the fuel cells has a significant influence on the total costs of energy generation. A range of lifetime estimates were deemed to be realistic. To find the impact of fuel cell lifetime on the LCOE, a sensitivity analysis has been made as shown in **Figure S15** for Curaçao and Viti Levu, respectively. For the LCOE of the fuel cells versus their lifetime, multiple cost scaling estimations are possible. For a grid lifetime of 20 years, fuel cells with a 10-year lifetime will need one replacement, whereas fuel cells with a lifetime of 9 years need two replacements, whereas 7 lifetime years are still left after 20 year. For fair comparison, the rest value of replaced equipment after its 20 years lifetime was withdrawn from total costs, assuming linear depreciation over its lifetime and corrected for the given discount rate. Furthermore, a Lang factor is present in the model, correlating bare equipment costs to estimated total costs. Therefore, two cases are presented, one including and one excluding the Lang factor for the replacement fuel cells after a certain amount of years.

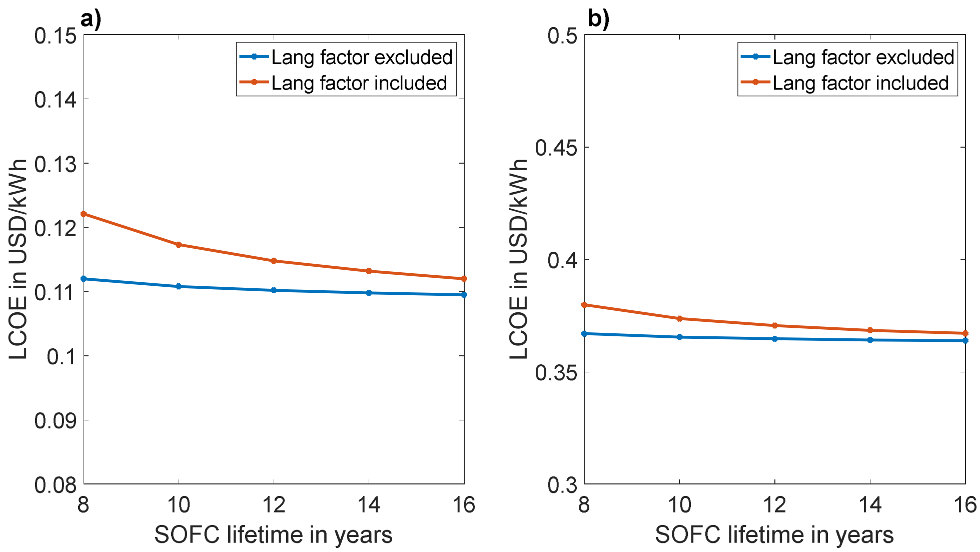

Figure S15. LCOE in USD/kWh versus SOFC lifetime, assuming 100% ammonia import at 500 USD/ton for a) Curaçao, b) Viti Levu.

Figure S15a Illustrates for Curaçao how the LCOE could decrease if SOFC lifetime increases. Depending on the calculation method to estimate replacement costs, this effect could either be significant, or will have a relatively modest effect on the overall costs. **Figure S15b** illustrates for Viti Levu, that the influence of SOFC lifetime on the LCOE will be modest. This is due to dominant influence of the windfarm costs on the overall costs. Therefore, for Viti Levu, focusing on decreasing windfarm generation costs is significantly more important.

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