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Tokenized Indexed-Green Bonds: Funding the Decarbonization of Ammonia Production

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Abstract: This study seeks to investigate how distributed ledger technology can be applied to the green bond market. Second, this study examines how green bonds can finance the suck cost of decarbonizing the ammonia industry. Third, this study seeks to forecast the spot price of ammonia. This forecast is relevant since the bond's coupon should be indexed and linked to the price of ammonia. The proposed tokenized indexed-green bond is a new idea that leverages the technologies of distributed ledgers, indexation, and green bonds. No study to current date has undertaken such research that integrates these technologies to fund the decarbonization of the ammonia industry. Data were collected on the spot price of ammonia from the Central Bank of Trinidad and Tobago online database at the monthly frequency over the January 1991 to June 2023 period. The applied forecasting methodology was a hybrid framework combining particle swarm optimization and support vector regression. This study found that an out-of-sample forecast for ammonia prices would be US$438.89/ton in the 1st quarter, US$289.99/ton by the 2nd quarter, US$448.30/ton by the 3rd quarter, and US $331.57/ton by the 4th quarter. The decarbonization of the ammonia industry is technically possible. Economically, it would involve leveraging several technologies such as green bond financing, tokenization, and indexation.

Keywords: green bonds, tokenization, distributed ledger technology, ammonia prices, decarbonization

1. Introduction

In 2015, 196 country parties signed a new international treaty to address climate change – the Paris Agreement. The Paris Agreement's goal is to stimulate collective action to combat climate change by limiting global warming to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C. The Agreement seeks to achieve its goal through the Parties implementing their action plans, called nationally determined contributions (NDCs) (Horowitz, 2016).

NDCs are based on countries' national circumstances and state the countries' intention to reduce greenhouse gas (GHG) emissions in specific sectors. Common sectors targeted in countries' NDCs include high GHG emitting sectors, such as heavy industry, electricity generation, transportation, agriculture, forestry, and waste management (Vogt-Schilb & Hallegatte, 2017). While the composition of the heavy industry sector will differ by country, many countries' heavy industry sector includes the petrochemical industry. Some countries' petrochemical industry includes the ammonia industry, which is a high GHG emitter.

Countries seeking to reduce GHG emissions from their ammonia industry are essentially requesting their ammonia producers to adopt measures to alter their manufacturing process. This can involve techniques such when applying carbon capture and storage (CCS), applying the hybrid synthesis of ammonia, and implementing the electrosynthesis of ammonia (Fasihi et al., 2021; Wang et al., 2021; Wu et al., 2021). The aforementioned measures involve high sunk costs.

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Debt financing can be used to fund the decarbonization of the ammonia sector. However, debt financing can be on unfavorable terms. Given these factors, green bonds emerge as an appropriate funding mechanism for the decarbonization of the ammonia sector. Moreover, indexed-green bonds whose coupon is linked to the spot price of ammonia can be used for financing.

Recently, the emergence of financial technology has allowed for innovations in the bond market (Gorkhali & Chowdhury, 2022; Liu et al., 2021). More specifically, blockchains[1] have been applied to bonds to improve their efficiency, and transparency, and reduce their operational costs. In this regard, there is an opportunity for ammonia producers to leverage tokenized green bonds to fund their ammonia decarbonization projects.

The objective of this study is threefold. First, this study seeks to investigate how distributed ledger technology can be applied to the green bond market. Second, this study examines how green bonds can finance the suck cost of decarbonizing the ammonia industry. Third, this study seeks to forecast the spot price of ammonia. The spot price of ammonia is relevant since the bond issuer must monitor and forecast the spot price of ammonia as it affects the coupon payout.

Notably, the tokenization of bonds is a new concept that has been applied only in a few instances. Furthermore, to date, there has been no application of tokenization to green bonds, indexed-green bonds, or any bond for the ammonia industry. The market

[1]A blockchain is a decentralized and ordered ledger designed to record transactions in a network. It operates through a chain of blocks, with each block containing a list of transactions, a timestamp, and a unique cryptographic hash connecting it to the previous block. This cryptographic linking ensures that any alteration to data in one block would necessitate modifying all subsequent blocks in the chain, making the blockchain immutable and highly resistant to tampering (Di Pierro, 2017).

for green bonds is still developing and the first green bond was only issued in 2007. Therefore, this study is novel as it applies the new concept of tokenization to green bonds as well as for financing the decarbonization of the ammonia industry.

The rest of this study is structured as follows. Section 2 presents a literature review on ammonia production and decarbonization, green bonds, and tokenization. This is followed by an outline of the data and methodology in Section 3. Section 4 presents the forecasting results. Section 5 facilitates a discussion and explores how tokenized green bonds can fund the suck cost of decarbonizing the ammonia industry. Section 6 concludes this study.

2. Literature Review

2.1. Steam methane reforming with the Haber–Bosch process (gray ammonia)

As previously mentioned, ammonia can be produced from several feedstocks, namely coal, crude oil, and natural gas. For coal, the first step involves burning it in the presence of oxygen to create a synthetic gas (syngas) (Chen et al., 2022; Smith et al., 2020). For crude oil, the first step involves heating it in the presence of oxygen to create naphtha as the syngas (Erisman et al., 2008; Smith et al., 2020; Yapicioglu & Dincer, 2019). For natural gas, the first step involves heating the gas to separate the methane from the other gases. Natural gas is the most common feedstock for the production of ammonia (Aasberg-Petersen et al., 2011; Smith et al., 2020).

Regardless of which feedstock is used, in general, the second step involves steam methane reforming (SMR). This involves heating the syngas in a reactor to produce hydrogen. More specifically, the primary reactor, the syngas (comprising methane and other gases), and steam are heated at high temperatures ranging from 850°C to 900°C and pressures ranging from 25 to 35 bar. This causes an endothermic reaction[2] in the presence of a catalyst. The energy required for this endothermic reaction is provided by the external combustion of methane fuel in furnace tubes that pass through the catalyst bed (Smith et al., 2020).

The secondary reactor is auto-thermal, meaning the heat generation process in the reactor is self-sustaining. Air is introduced and compressed in the secondary reactor where it facilitates the partial oxidation of the reagents (methane and steam) at temperatures ranging from 900°C to 1000°C. The partial oxidation reaction of methane and steam with air produces heat, which serves as the heat source for the reaction, hence the reason why the process in this reactor is auto-thermal (Smith et al., 2020).

The output from the secondary reactor is comprised of carbon monoxide, hydrogen, unreacted steam, and methane. This mixture is sent to the two-stage water-gas shift (WGS) reactor. The purpose of the WGS reactor is to maximize the conversion of carbon monoxide to hydrogen. In the WGS reactor, the carbon monoxide is endothermically reacted with steam to produce carbon dioxide and additional hydrogen. This conversion is important since hydrogen is the desired product for ammonia synthesis (Smith et al., 2020).

After the WGS reaction, the carbon dioxide is removed from the gas mixture utilizing solvents to selectively capture and separate the carbon dioxide from the gas stream. This results in a purified hydrogen gas stream. Next, a methanation reactor[3] is employed to minimize the risk of poisoning the catalyst (Smith et al., 2020).

[2]An endothermic reaction is a chemical reaction that involves the absorbing of heat.
[3]A methanation reactor converts any remaining carbon dioxide into methane.

In the downstream synthesis loop, argon, an inert gas, tends to accumulate along with methane that was unreacted from earlier stages. These gases need to be periodically purged to maintain the desired composition and efficiency of the system (Smith et al., 2020).

In the ammonia production stage, the Haber–Bosch reactor is used to facilitate the reaction between hydrogen and nitrogen to produce ammonia (Humphreys et al., 2021). The reaction occurs under high pressure ranging from 15 megapascals (MPa) to 25 MPa, and elevated temperatures ranging from 400°C to 450°C. Magnetite or wustite is employed as an iron-based catalyst to enhance the reaction rate (Smith et al., 2020).

Only a small portion of the hydrogen and nitrogen react to generate ammonia during a single pass of the hydrogen through the reactor.[4] A gas recycling system is put in place to get around this limitation and enhance overall ammonia production. The gas recycle system sends the gases (the unreacted hydrogen, nitrogen, and other gases) for another pass through the system. These additional passes allow the system to achieve higher overall conversion rates (Smith et al., 2020).

The majority of carbon dioxide emissions in the SMR-HB process come from SMR (Winter & Chen, 2021). Therefore, carbon dioxide emissions will emerge from the SMR and WGS processes due to the inherent carbon content in methane and the combustion of methane during the reforming reaction.

Several strategies can be employed to minimize the carbon dioxide emissions from the SMR-HB process. The techniques can be classified as follows: (i) SMR-HB integrated with carbon capture, storage, and use (CCSU) and (ii) electrolysis of water (Ghavam et al., 2021; Smith et al., 2020; Wang et al., 2021). The first approach, which is also referred to as blue ammonia, involves capturing the carbon dioxide emissions that were generated from the ammonia production process and storing it in natural or artificial reservoirs in the ground.

The second approach, which is also referred to as green ammonia, involves producing ammonia through the combination of the electrolysis of water to produce hydrogen with the Haber–Bosch process[5] (Ghavam et al., 2021; Wang et al., 2021).

The blue and green ammonia production processes involve high costs. Ayodele et al. (2020) estimated the total capital costs for the SMR-HB process with carbon capture at US$831 million. Green ammonia production costs can be around US$500 million. However, the total capital cost for SMR-HB without carbon capture was estimated at US$241 million.

These high suck costs to decarbonize ammonia production provide justification for the use of green bonds. The next subsection reviews green bonds.

2.2. Green bonds

Multinational ammonia companies are likely to use long-term debt financing for decarbonization projects. This is due to these projects requiring high upfront sunk costs and a long period would be required for the payback. Therefore, project developers are likely to use debt financing as it allows them to amortize the cost of the project over its life cycle. Given this, a green bond can be used as an instrument for debt financing.

A green bond is a fixed-income security that can be used to finance projects with environmental benefits. It has the main

[4]The Haber–Bosch process has a low equilibrium single-pass conversion rate. Approximately 15% of the hydrogen is converted in the single-pass.
[5]In 1909, Fritz Haber and Carl Bosch developed a process, which involved the conversion of hydrogen gas into ammonia by reacting it with nitrogen. This process became known as the Haber–Bosch process (Kandemir et al., 2013; Smith et al., 2020).

components of a traditional bond, such as a par value, a coupon, and a maturity date. However, its main difference from a traditional bond is that its proceeds are used for projects with environmental benefits (Cheong & Choi, 2020; Tolliver et al., 2020; United Nations, 2017).

An indexed bond is a bond whose coupon is linked to the price of an underlying (Kang, 2020). Indexed-green bond refers to green bonds linked to the price of another asset (Hassani & Bahini, 2022). In this case, the coupon can be linked to the spot price of ammonia. This would be attractive to investors as it can allow investors to earn higher coupons when the spot price of ammonia is high. Likewise, it can result in the bond issuer paying lower coupons when the spot price of ammonia is low.

There are several key features of a green bond.

First is the purpose and use of proceeds. As just mentioned, the distinguishing feature of green bonds is the use of proceeds. The funds raised through the issuance of green bonds are earmarked for projects that have positive environmental impacts. In the context of the ammonia industry, these projects can include upgrades for the integration of CCSU with the Haber–Bosch process. Projects to produce green ammonia from the electrolysis of water can also be funded with green bonds (United Nations, 2017).

Second is the certification and verification of the bond. The International Capital Market Association has guidelines for the issuance of green bonds. These guidelines, which are referred to as the green bond principles (GBPs), include requirements for the green bonds to undergo a rigorous certification or verification process to ensure transparency and credibility. External independent third parties acting as verification agencies are used to validate green bonds. This independent verification and certification assure investors that their investment is being utilized for projects that benefit the environment (United Nations, 2017).

Third is the coupon. The coupon of a bond is primarily determined by market conditions, the creditworthiness of the issuer, and the perceived level of risk associated with the bond. For a green bond, the investor/bondholder may have altruistic values toward the environment. Subsequently, they may be willing to accept a lower interest rate for a green bond than a traditional vanilla bond, once they are assured that the proceeds are used for the intended purpose (United Nations, 2017).

Fourth is the maturity. The maturity of green bonds is not inherently different from conventional bonds. However, the bond issuers may be able to negotiate longer maturity periods with the investors (United Nations, 2017).

Fifth is the reporting. Green bonds typically have reporting requirements (United Nations, 2017). For an ammonia decarbonization project, a green bond issuer will likely be required to disclose detailed information on: (i) how the proceeds from the bond issuance are allocated and utilized; (ii) the project evaluation to determine the profitability of the project; (iii) how much carbon dioxide emissions are removed; and (iv) the environmental impact of the project.

Green bonds can help ammonia companies tap into a broader investor base comprising socially responsible and sustainability-focused investors actively seeking opportunities to support sustainable initiatives. This expanded access to financial capital, especially at preferential terms, can accelerate the implementation of decarbonization projects.

Efficiency gains[6] can be achieved through the issuance of green bonds on distributed ledgers. The next subsection discusses this application.

[6]Tokenized bonds can reduce transaction costs of bonds and enhance transparency and the availability of credible bond data.

2.3. Review of asset tokenization

A token refers to a digital representation of an asset, utility, or value that is issued and managed on a blockchain network. A token can be a digital currency such as Bitcoin, or it can be ownership of assets. The asset can be a digital asset, such as a stock and bond, or a representation of ownership of a physical asset, such as a house or car (in the case of a house, the token will be analogous to a digital deed or lease).

Asset tokenization involves the representation of physical assets or conventional financial instruments like stocks, options, and futures on distributed ledgers. This digital depiction serves to enable secure and decentralized transfers, ownership, and trading of assets, all while maintaining efficiency (Mounira, 2023).

Distinctions can be made between tokenized assets that are off the chain and tokens that are “native” to the distributed ledger.

The first type is known as real asset tokenization (Tian et al., 2020). In this form of tokenization, existing tangible assets are transformed into digital tokens on a distributed ledger. This process involves associating the economic value and corresponding rights of these assets with digital tokens that are generated on a distributed ledger or blockchain (Popescu, 2020; The Organisation for Economic Co-operation and Development, 2020).

Tokens created through asset tokenization are present on the blockchain and represent the rights to the underlying assets, effectively functioning as a form of value storage. However, the physical real-world assets remain external to the blockchain. To ensure consistent backing of these tokens, the assets are typically placed in custody (Mounira, 2023). Theoretically, any asset can be tokenized and its rights can be represented on a distributed ledger (Hargrave et al., 2019; The Organisation for Economic Co-operation and Development, 2020).

Tokens that are native to the distributed ledger are digital assets that only exist on the distributed ledger. For example, cryptocurrencies such as Bitcoin and Ethereum are native as they only exist on their respective distributed ledger. Tokens issued in initial coin offerings, as well as financial assets, are also native as they exist only on a distributed ledger (The Organisation for Economic Co-operation and Development, 2020).

A few stakeholders have issued tokenized bonds. For instance, in 2018, the World Bank launched the first tokenized bond on a distributed ledger technology network. The pioneering initiative, which it referred to as bond-i, was issued in partnership with the Commonwealth Bank of Australia (CBA). The project raised A $110 million (Mounira, 2023).

The process began with pre-authorized investors accessing the private blockchain, which was controlled by the World Bank and the CBA.[7] The investors used their authentication keys and submitted their bids; the World Bank closely monitored the auction process in real time. Bond issuing, paying, and settlement were managed by CBA. Smart contracts were used for the automation of coupons to the bondholder investors (Mounira, 2023; The Organisation for Economic Co-operation and Development, 2020).

In 2018, Nivaura issued tokenized bonds in the United Kingdom’s Financial Conduct Authority Sandbox. The issuance involved two bonds. First was the Control Bond, which was a GBP-denominated bond that was issued and registered on traditional clearing systems. However, the transfer of the rights to the Control Bond was done through a token on a blockchain. The payment of coupons was also done on the blockchain (The Organisation for Economic Co-operation and Development, 2020).

[7]The blockchain was maintained by the CBA, located in Sydney (Mounira, 2023; The Organisation for Economic Co-operation and Development, 2020).

The second was an Ethereum-denominated bond that was fully registered, cleared, and settled on a public blockchain. Nivaura, the bond issuer, also acted as the custodian for the tokenized bond. The blockchain acted as the registrar for the bond, and smart contracts were used to automate the delivery of the bonds and the payment of coupons and principal. This eliminated the need for third parties and also improved the efficiency, transparency, and speed of the overall bond management process (The Organisation for Economic Co-operation and Development, 2020).

In 2021, the European Investment Bank issued its first tokenized bond. It issued its second tokenized bond in 2022 (Hall, 2023). In 2022, the Inter-American Development Bank issued a 2-year US$10 million blockchain-based bond. In the bonds, smart contracts were used for issuance, purchase, sale, and settlement (Inter-American Development Bank, 2022).

Indeed, the benefits of financial asset tokenization are manifold. Firstly, it can significantly enhance liquidity by permitting fractional ownership, allowing even smaller-scale investors to partake in asset ownership and trade smaller units of valuable assets. This decentralization of access holds the potential to broaden the base of investors, as many small investors can purchase the investment instrument. Secondly, tokenization reduces costs and enhances efficiency by cutting out intermediaries from both the issuance and trading processes. Smart contracts, thanks to their automation, streamline administrative duties, simplify paperwork, and expedite transaction settlements. Moreover, asset tokenization provides amplified transparency and security due to blockchain technology's inherent characteristics. Transactions are traceable, immutable, and resistant to tampering, thus minimizing fraud risks and fostering increased trust in the system. Furthermore, the worldwide accessibility of digital tokens facilitates cross-border investments, allowing seamless and frictionless transactions on a global scale (Pana & Gangal, 2021; Schletz et al., 2020). These characteristics encourage the tokenization of bonds.

The next section reviews the data and the methodology to forecast the price of the underlying (ammonia) for the indexed-green bond.

3. Data and Methodology

As previously mentioned, indexed-green bonds are bonds whose coupons are linked to the spot price of an asset. This paper proposes that ammonia producers issue an indexed-green bond to mobilize finance to fund their decarbonization projects. The indexed-green bond can be linked to the spot price of ammonia. Therefore, to determine how much coupon must be paid, the ammonia producers must monitor and forecast the spot price of ammonia.

3.1. Data

Data were collected on the spot price of ammonia from the Central Bank of Trinidad and Tobago (CBTT) online database. Such data were available on the CBTT since the country, Trinidad and Tobago (T&T), exports ammonia. Data were available at the monthly frequency over the January 1991 to June 2023 period. This produced a total of 392 observations.

3.2. Methodology

Before forecasting is performed, this study tests the data for linearity and normality. This testing is important since if these assumptions do not hold then a model must be selected that can perform well under those conditions.

Forecasting methodologies can be characterized as linear or non-linear. Traditional econometric models such as the autoregressive integrated moving average and the generalized conditional heteroscedasticity can perform a univariate forecast of a time series. However, the aforementioned models perform poorly when the assumption of linearity and normality does not hold.

To address non-linear dynamics, machine learning models have been used in economics. A hybrid framework that combines two models can be used for non-linear forecasting. The proposed hybrid framework combines particle swarm optimization (PSO) and support vector regression (SVR).

3.2.1. PSO

PSO functions as an optimization technique by simulating the flocking and swarming behaviors observed in nature, such as birds and insects. It leverages a group of candidate solutions called particles, each representing a potential solution in a multidimensional search space. These particles move iteratively through the search space, adjusting their positions based on their own historical best performance and the collective best position found by the entire group. As particles collaborate, they converge toward the optimal solution or a near-optimal solution in the search space, making PSO an effective method for solving optimization problems (Kennedy & Eberhart, 1995).

The optimization procedure commences with a swarm comprising N particles, where every particle possesses both a position vector and a velocity vector (Liu et al., 2018; Rastgoufard & Charalampidis, 2018; Wang et al., 2010). This is indicated as follows:

$$x_i = (x_{i1}, \ldots, x_{id}) \tag{1}$$

$$v_i = (v_{i1}, \ldots, v_{id}) \tag{2}$$

where x_i is the position vector, v_i is the velocity vector, and $i = 1, \ldots,$ d refers to the number of dimensions in each vector.

Every individual particle is cognizant of its individual best position (ob) as well as the globally best position (gb) within the D-dimensional search space. The updated velocity and position of each particle are computed using the following formulas:

$$v_{id}^{k+1} = \omega v_{id}^{k} + c_1 r_1 (ob - x_{id}) + c_2 r_2 (gb - x_{id}) \tag{3}$$

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \tag{4}$$

where k denotes the previous velocity or position, $k+1$ denotes the new velocity or position, ω signifies a weight, c_1 represents the cognition factor, c_2 denotes the social learning factor, the coefficient c shows the force exerted by each particle toward its individual best (ob) and the global best (gb) positions, and r_1 and r_2 correspond to uniformly distributed random numbers within the range of 0–1.

The weight responsible for balancing the trade-off between global and local exploration was initially established to decrease linearly within the range of 0.9–0.4. However, the current approach involves estimating the weight using the following formula:

$$\omega = \omega_{min} - (\omega_{max} - \omega_{min}) * \frac{iter}{iter_{max}} \tag{5}$$

where ω_{max} is the maximum weight, ω_{min} is the minimum weight, *iter* is the current iteration, and $iter_{max}$ is the maximum iteration.

3.2.2. SVR

SVR is an extension of the support vector machine (SVM). While the SVM was initially designed for classification tasks, SVR applies the same fundamental principle of hyperplanes to perform regression. In SVM, the goal is to find a hyperplane that effectively separates different classes in a classification problem while maximizing the margin between them. Similarly, in SVR, the objective is to find a hyperplane that best fits the data points in a regression context.

The non-linear representation of a SVR can be expressed by:

$$y_i = w^T \Phi x_i + b \tag{6}$$

where w denotes the weight vector, Φ denotes a non-linear parameter, b denotes the intercept, and x_i denotes the input matrix.

The w and b parameters are estimated by minimizing the function

$$r(C) = C\frac{1}{N}\sum_{i=1}^{N} L_\varepsilon(d_i, y_i) + \frac{1}{2}||\omega||^2 \tag{7}$$

where

$$L_\varepsilon(d, y) = \begin{cases} |d-y| - \varepsilon & \text{if } |d-y| \geq \varepsilon \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

where C denotes the regularized constant that determines the trade-off between the empirical risk and the regularization term; ε shows the tube size, which states the approximation accuracy placed on the training data points; and $L_\varepsilon(d, y)$ represents the ε-insensitive loss function.

The PSO is integrated with the SVR by performing as the activation function to determine the best values for the regularization parameter C, the tube size of insensitive loss function ϵ, and the kernel function parameter K.

3.3. Methodology limitation

Importantly, machine learning models such as the SVR carry a limitation. They are black box models. A researcher inputs the data and runs the regression, but the model does not produce coefficients like traditional linear regression models.

Despite this limitation, machine learning models like the SVR can still be used since they can be assessed for model authenticity with a series of predictive accuracy tests. This study applies these tests.

The next section presents the results of the forecasting.

4. Results

4.1. Pretesting

The first pretest that is performed is the Jarque–Bera (JB) test. The results are in Figure 1. The probability of the JB statistic was 0.00. This suggests the rejection of the null hypothesis of normality manifested by the skewness and excess kurtosis being zero. This result suggests that ammonia prices are not normally distributed.

Next, the Bai and Perron test is performed for structural breaks. See Table 1.

The results of the Bai–Perron test suggest that there are four structural breaks. This is evidenced as the null hypothesis of four structural breaks is not rejected in favor of the alternative hypothesis of five breaks. The existence of structural breaks confirms that ammonia prices are non-linear. Thus, the existence of non-normality and non-linearity justifies the use of a machine learning model to forecast ammonia prices.

The next subsection provides the results of the diagnostics.

4.2. Diagnostics

A response plot provides a visual comparison between a model's predictions and the actual observed values. As can be seen in Figure 2, the PSO-SVR performed well within sample as the predicted values were very close to the actual values.

A predictions response plot also provides a visual comparison between a model's predicted values and the actual observed values. However, it includes a regression line that shows the perfect predictions, which can be compared with the actual data. In other words, it visually shows how far off were the inaccurate predictions.

Figure 1
Jarque–Bera test

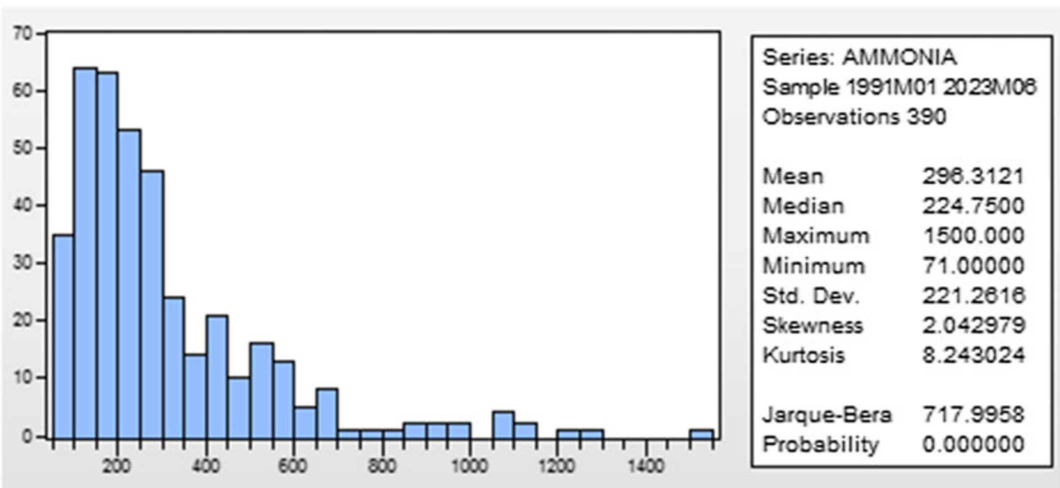
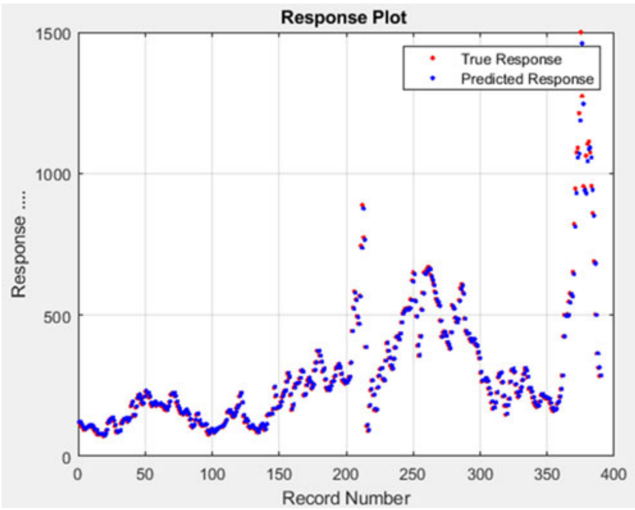


Table 1
Bai–Perron tests of L+1 vs. L sequentially determined breaks

Sequential F-statistic determined breaks:				4
Break test	F-statistic	Scaled F-statistic	Critical Value**	
0 vs. 1 *	204.9377	204.9377	8.58	
1 vs. 2 *	21.47062	21.47062	10.13	
2 vs. 3 *	12.20120	12.20120	11.14	
3 vs. 4 *	15.63885	15.63885	11.83	
4 vs. 5	0.763164	0.763164	12.25	
Break dates:				
	Sequential	Repartition		
1	2007M12	2003M02		
2	2003M02	2008M01		
3	2018M09	2013M11		
4	2013M11	2018M09		

* Significant at the 0.05 level.
** Bai–Perron (Econometric Journal, 2003) critical values.

Figure 2
Response plot



As can be seen in Figure 3, the PSO-SVR had high predictive accuracy as the imperfect predictions were close to the actual observations.

A regression plot visually shows how well the relationship between the independent variable (predictor) and the dependent variable (target) in a dataset is fitted with a model. In Figure 4, the R is equal to 0.9723, suggesting that 97.23% of the proportion of the total variability in the dependent variable is explained by the model. This also suggests the model has high predictive accuracy.

An error histogram, also known as a residual histogram, is a graphical representation that shows the distribution of errors or residuals in a predictive model. The X-axis of the histogram

Figure 3
Predictions response

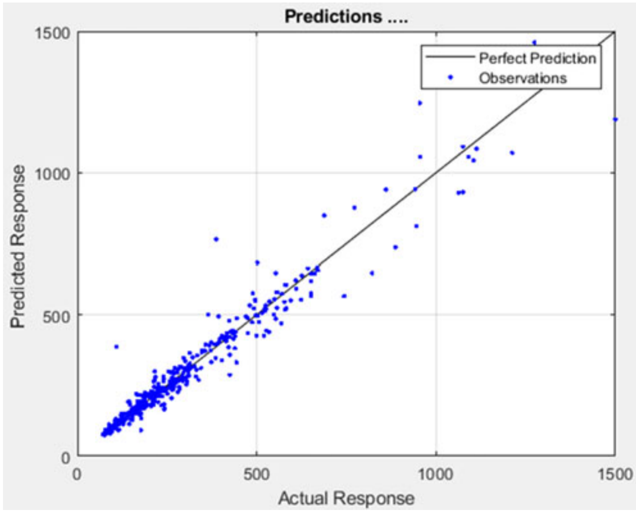
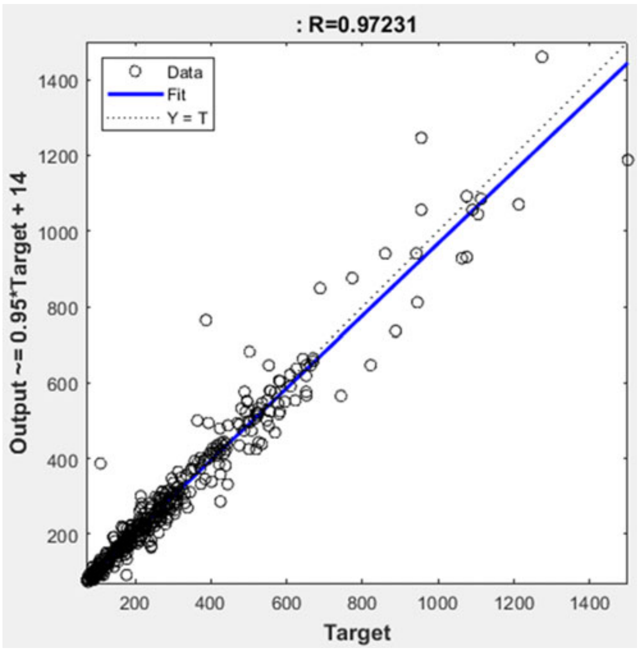


Figure 4
Regression plot

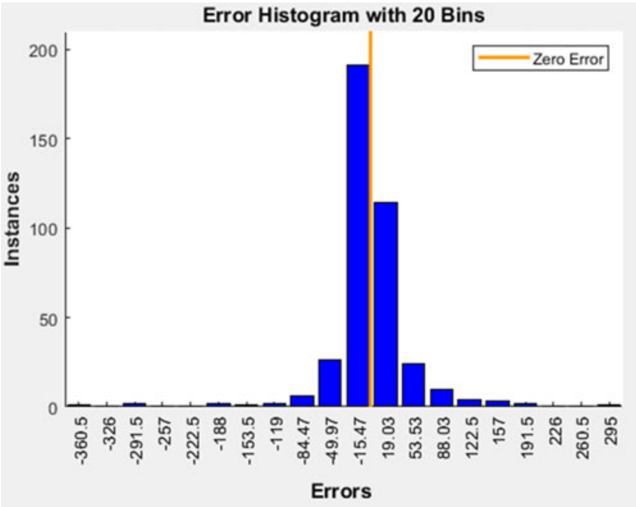


represents the range of error values. The Y-axis represents the frequency or count of data points that fall into each error bin.

In Figure 5, the error histogram is symmetrically distributed around zero, suggesting that the model's predictions are relatively balanced, positive errors cancel out negative errors, and the errors are centered around zero.

The next subsection presents the forecasts.

Figure 5
Error histogram



4.3. Forecasts

A 12-step ahead out-of-sample forecast for the ammonia prices is displayed in Table 2.

Table 2
Out-of-sample forecast for the ammonia prices

Month 1	436.65
Month 2	260.23
Month 3	438.89
Month 4	275.34
Month 5	441.61
Month 6	289.99
Month 7	444.75
Month 8	304.23
Month 9	448.30
Month 10	318.08
Month 11	452.22
Month 12	331.57

While the ammonia prices are forecasted 12 months ahead, the highest frequency the coupon can be paid is quarterly. Therefore, the forecasts for every 3 months are relevant.

The out-of-sample forecast for ammonia prices in month 3 is US $438.89/ton. The forecast for month 6 is US$289.99/ton. The forecast for month 9 is US$448.30/ton. The forecast for month 12 is US$331.57.

These forecasts can inform the bond issuers to estimate the expected costs of coupon payouts.

The next section discusses the tokenization of indexed-green bonds.

5. Discussion of the Tokenized Indexed-Green Bonds

Tokenized indexed-green bonds can be used by ammonia producers to fund their decarbonization projects. Tokenization should be adopted as it presents an opportunity to improve the efficiency, transparency, and security of the bond issuance while minimizing costs. The bond can be indexed, which allows the coupon payment to be variable. This is attractive to potential bondholders when the underlying's (ammonia) prices are high, and beneficial to the bond issuer when the underlying's prices are low. Additionally, the bond should be a green bond since its principal will be used to fund decarbonization projects. This should help the bond issuers mobilize capital with a favorable maturity.

Several factors must be considered in the tokenized green bond. They are discussed in the following subsections.

5.1. Issuance, denomination, and fragmentation

Tokenized green bonds can be issued in two ways. The first way is where the bond is issued traditionally.[8] Then, tokens are created to symbolize the bond. The tokens are sold to investors. Then, each token holder becomes a bondholder.

The second way is where the tokenized bond is directly issued on the distributed ledger. The tokenized bond is registered on a distributed ledger. The bond can be denominated in a major currency or a cryptocurrency. An initial public offering is performed, and the investor may purchase the tokenized bond. The tokenized bond may also be fragmented, allowing small-scale investors to purchase smaller units of the bond than what would be available under a traditional bond offering.[9] This allows the tokenized bond to mobilize funds from a wide pool of investors.

Then, all transactions, settlements, transfer of ownership, payment of coupons, etc. are done on the distributed ledger. The automation achieved through smart contracts reduces costs throughout the bond's lifetime, benefiting issuers and investors alike.

5.2. Regulation

Tokenized bonds bring benefits of increased transparency, immutability, and security, features that are inherent in distributed ledger technology. The transparency feature is particularly attractive as it will allow bond issuers to comply with know-your-customer, anti-money laundering, and counter-financing of terrorism measures, which are typically imposed upon financial agencies in different jurisdictions.

Permissioned distributed ledger networks allow for easier AML/KYC checks and implementation of privacy requirements. In contrast, public networks facilitate greater decentralization and offer greater resilience due to the larger number of nodes in the network and the absence of a single point of failure. From a regulatory perspective, it is difficult to regulate a fully decentralized system without a single point of contact to apply the regulation. For this reason, financial regulators would prefer potential bond issuers to use permissioned distributed ledger networks.

5.3. Secondary markets

The tokenized bond can be traded on the secondary market. The secondary market can be an exchange that enables distributed ledger technology.

On decentralized exchanges, order matching, clearing, and settlement occur through the use of smart contracts. As previously mentioned, there is no single point that is responsible for the operation of the exchange on a fully public and decentralized

[8]The traditional bond issuance process involves the issuer hiring an investment bank to underwrite the bond. The issuer or the investment bank then files a registration with the securities regulator for the jurisdiction. The registration document must disclose all material information about the bond. The bond is offered to investors through an initial public offering. The investors purchase the bond and become bond holders, and the proceeds are transferred from the investment bank to the bond issuer.

[9]If the fragmented bonds do not sum to the original value of the pre-fragmented bond, it will give rise to arbitrage opportunities.

distributed ledger. This raises questions about the application of financial regulations.

In practice, most distributed ledger-enabled exchanges are operated by a central actor that sets up the platform and the order book. Therefore, the exchanges are not absolutely decentralized as they claim to be.

5.4. Custody

As previously mentioned, in the tokenization of physical assets, the physical asset is placed in the custody of a custodian to ensure that the token retains its backing.

In the case of a tokenized bond, the custody is based on a "self-custody"; thus, no central securities depository is needed. Therefore, the custodian's responsibility is to keep the distributed ledger access keys to the bonds safe. A central body can act as the custodian. Therefore, the distributed ledger would not be fully decentralized.

5.5. Liquidity

Tokenized bonds can be traded on a distributed ledger technology-based exchange 24/7. Therefore, they are more liquid than some securities. Furthermore, tokenized bonds may benefit from a lower illiquidity premium[10], which allows the bond to trade at a price closer to its fair value.

Liquidity for the tokenized bond can also be achieved through trading of the bond on the secondary market. The benefit of improved liquidity could be an increased flow of funds into the investment.

Market readiness is a requirement for the smooth operation of the tokenized bond market as investors must be willing to participate in this relatively new investment mechanism. Market readiness will create demand and liquidity for the tokenized bonds.

5.6. Price of underlying and indexed interest rate

The coupon payments are linked to the price of an underlying for indexed bonds. There are two main ways in which this is implemented. The first is where the coupon payments are linked to a fixed interest rate, such as the US Treasury yield. This study does not recommend the first approach.

The second approach is where the coupon is linked to the spot price of an underlying. Consider an example, assume a person buys a tokenized bond with a coupon rate of 5% of ammonia's price. So if ammonia is trading at $100/ton, then the coupon payment will be $5. If the spot price of ammonia rises to $500 on the payout date, then the coupon payment would be $25.

Therefore, if the spot price of the underlying increases, the coupon will increase. Likewise, if the spot price of the underlying decreases, the coupon will decrease. The coupon can be paid out quarterly, semi-annually, or annually.

Investors seeking to generate income would be interested in bonds with higher frequency payouts for the coupons. Additionally, investors and bond issuers would be interested in the spot price of the underlying for the indexed bonds.

Bond issuers and bondholders would be interested in forecasts of the spot price of the coupon on the payout dates as it affects the amount of the coupon. For bond issuers, this information can help them plan in advance the cost of issuing the bond. This information can be included in their net present value analysis to determine the profitability of projects.

[10]Illiquidity premium is the premium over the face value of the bond. This premium is charged to compensate the bond holder as the bond is relatively illiquid and difficult to sell.

5.7. The legality of smart contracts

Smart contracts are programs that execute the terms of a contract when predetermined terms and conditions are met. They can be used to automate many processes surrounding the management of the tokenized bond. However, the legal status and enforceability of smart contracts under private law may be questionable as many jurisdictions have not developed laws to address distributed ledger technology and its application.

This issue is important since if digital assets on a distributed ledger are not recognized as assets under private law, they cannot be owned. Moreover, if a law does not recognize a smart contract as a binding legal obligation, then smart contracts will not be enforceable if there was a technology error or breach. This risk can deter potential investors from tokenized indexed-green bonds.

5.8. Consensus mechanisms

Consensus mechanisms, such as proof-of-work (PoW)[11] that is used by blockchain, are required to validate new transactions and add them to the network. The PoW validation mechanism is relatively slow and highly energy-intensive given that a high amount of power is consumed by the miners as they validate transactions. For this reason, a proof-of-stake consensus mechanism should be used to validate transactions.

The next section concludes this study.

6. Conclusion

Recall, the first objective of this study was to investigate how distributed ledger technology can be applied to the green bond market.

The utilization of distributed ledger technology can create facilitating the issuance, trading, and management of green bonds. The bonds can be issued in two ways. First, the traditional method can be used to issue and register the bond with a securities regulator. Then, the distributed ledger is used to create a token that represents the rights to the bond. The token could then be sold to investors, thus making them bondholders. In the second option, the bond can be issued and completely managed on the distributed ledger.

Traditional bonds typically require a high capital investment, which can be prohibitive for small-scale investors. This can be addressed by fragmentation, where the tokenized bonds are subdivided into smaller units for sale. Fragmentation allows a wide range of investors to purchase the bond, thus enabling the bond issuer to successfully mobilize finance.

The tokenized bond can be issued on a private or public distributed ledger. However, to ensure compliance with financial regulations, there should be a central operator to which responsibility can be placed. For this reason, a private distributed ledger can be selected. Furthermore, the central operator can act as the custodian for the access keys for the tokenized bonds on the distributed ledger. This self-custody allows the bond issuer to save on costs as they will not have to hire a third party for this service.

Liquidity for the bond can be achieved as the bond is traded on the secondary market. Liquidity is also achieved as the tokenized bonds can be bought and sold at any moment on the distributed ledger exchange.

Another important consideration that arises is the legality of smart contracts. The application of distributed ledger technology to

[11]In PoW, the first miner to solve the puzzle to validate a transaction is rewarded with a unit of the cryptocurrency. This competition between the miners involves wastage as all the miners other than the first miner to solve the puzzle will not be rewarded. In PoS, miners do not compete to solve the blocks. Rather, validators are randomly selected to add new blocks to the blockchain.

securities is relatively new, and many jurisdictions have not yet developed laws to address the issue. This raises a risk that smart contracts may not be enforceable if a jurisdiction does not have laws to recognize digital assets. Nevertheless, most jurisdictions do recognize the terms of a contract may be expressed and recorded in different forms. Therefore, dispute resolution and arbitration for the enforcement of smart contracts are presently uncertain.

Consensus on the distributed ledger can be undertaken by the proof-of-stake mechanism. This allows for energy-efficient mining as transactions are validated. Additionally, as the distributed ledger technology is secure, transparent, fast, and immutable, it allows the operation of the tokenized bond to inherit these characteristics.

The second objective of this study was to examine how green bonds can finance the suck cost of decarbonizing the ammonia industry.

Green bonds emerge as the appropriate financing mechanism for decarbonizing the ammonia industry due to the cost structure of the decarbonization projects. Decarbonization projects involve activities such as integrating the SMR process with CCS or producing ammonia through the electrolysis of water. Both approaches involve high suck costs, which extend to the hundreds of millions. These costs are so high, that it would take a long time for a solvent company to fully recover them. Given that the projects will last a long period, it is rational for an ammonia project developer to seek to spread these costs over the project's lifecycle. Thus, the project developer may opt for a debt financing mechanism with a long maturity structure.

Green bonds are also appropriate as some investors are interested in environmental conservation. Therefore, once the proceeds of debt will be used for an environmental cause, altruistic investors will be willing to provide the finance on favorable terms. In the case of ammonia decarbonization projects, the desired favorable terms would be a long maturity and a low coupon rate. But the coupon should be linked to the underlying rather than the par value of the bond.

The third objective of this study was to forecast the spot price of ammonia. Unlike traditional fixed-rate bonds, the coupon of the indexed bond can be applied to the spot price of the underlying. In this case, the underlying is the spot price of ammonia. Therefore, a forecast of the spot price of ammonia would be of interest to the bond issuers and bondholders as it affects the coupon payout. Additionally, the coupon payout can be included as a cost in the evaluation of the profitability of decarbonization projects.

This study found that an out-of-sample forecast for ammonia prices would be US$438.89/ton in the 1st quarter, US$289.99/ton by the 2nd quarter, US$448.30/ton by the 3rd quarter, and US$331.57/ton by the 4th quarter.

The decarbonization of the ammonia industry is technically possible. Economically, it would involve leveraging several technologies such as green bond financing, tokenization, and indexation. Through the application of these innovations, ammonia companies can effectively communicate their commitment to sustainable practices and embark on a transition to the low-carbon economy.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

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