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Blockchain Electricity Trading Using Tokenised Power Delivery Contracts

Mel T. Devine, Marianna Russo and Paul Cuffe, *Member, IEEE*

***Abstract*—This paper proposes a new mechanism for forward selling renewable electricity generation. In this transactive framework, a wind or solar farm may directly sell to consumers a claim on their future power output in the form of nonfungible blockchain tokens. Using the flexibility of *smart contract* code, which executes irrevocably on a blockchain, the realised generation levels will offset the token holders' electricity consumption in near real-time. To elucidate the flexibility offered by such smart contracts, two ways of structuring these power delivery instruments are considered: firstly, an exotic *tranched* system, where more senior tokens holders enjoy priority claims on power, as compared against a simpler *pro-rata* scheme, where the realised output of a generator is equally apportioned between token holders. A notional market simulation is provided to explore whether, for instance, consumers could exploit the flatter power delivery profiles of more senior tranches to better schedule their responsive demands.**

I. Introduction

THIS paper explores how *claims* on future electricity production can be directly traded between generators and consumers through blockchain in a cyber-physical marketplace. While a literature is emerging on tokenised paradigms [1], [2] for peer-to-peer trading of electrical energy [3], the market framework proposed here takes an alternative structure, where power contracts for future delivery [4] are transacted on the blockchain. These claims on future generation could be embodied as nonfungible blockchain tokens [5], with future electrical power delivery as the underlying asset [6], [7]. Therefore the claims can be qualified as a cyber-physical forward contract for a blockchain application within a decentralised electricity markets [8].

The increased demand for power system flexibility, driven by less passive buyers and more active users, is resulting in more complex interactions in the distribution network, e.g. demand side management and distributed energy resources [9], [10]. With the progressive phase-out of renewable energy subsidies [11], peer-to-peer mechanisms for forward trading could have significant value in offering the flexibility required to coordinate more complex generator-load dynamics [4], and can likewise stabilise revenues for renewable generators in the transition towards sustainable power systems. As subsidies expire and renewable energy penetration increases, the value that renewable generators are able to capture in the centralised (wholesale) market is decreasing, especially in those areas where renewable installed capacity and generation profile are more (and positively) correlated with the amount of national subsidies, as in Europe [12] and China [11].

In recent years, research has emerged which focuses on evaluating the potential of the so-called *energy internet* (i.e. the synergistic combination of renewable energy sources and information technologies) as an instrument for the flexible and economic management of distributed energy systems [10], [13], [14]. In such systems, electricity is generated by maximising the exploitation of renewable sources in a distributed fashion and so to dynamically adjust the electricity utilisation within the grid [15] [16].

Blockchain represents a promising new technology for energy management, automated control and energy trading in the decentralised and distributed framework of the energy internet. Modern blockchains [17] allow financial arrangements of arbitrary complexity [18] to be embedded as scripts, often called *smart contracts* or *chaincode*, which execute in a decentralised fashion beyond the interference of any one party. This would allow tokenised power delivery claims to be immutably settled in near real-time with zero counter-party risk (see [19] for more on this disruptive paradigm).

Blockchain-enabled smart contracts have been exploited in the context of decentralised systems and secure peer-to-peer trading to facilitate demand response [10], [20], [21]. As one speculative proposal for how the flexibility of such smart contracts could be exploited, this paper proposes a novel way to apportion the real-time output of a generator between diverse token holders: *tranching*. This novel tranching structure is proposed firstly to explore its usefulness for managing the volatility of power delivery, and also as a case study of the exotic new instruments that blockchain technology could support in a cyber-physical electricity marketplace.

Under the proposed tranching structure, a generator's real-time output is continuously divided into a *senior*, a *middle* and a *junior* tranche. All power produced below a certain threshold is first allocated to the senior tranche: only when this level is exceeded does the middle tranche gain a claim on the power, and likewise for the junior tranche. Notably, the shape of these tranches' outputs will be quite different. As the senior tranche can be anticipated to provide uninterrupted blocks of constant power over sustained periods, it may facilitate the activation of responsive demands that have inter-temporal constraints or cycling costs (e.g charging a battery, where it is undesirable to interrupt the charging once it has begun) Tranches are not fungible and therefore allow renewable generators to target power delivery contracts to particular market segments: this overcomes the anonymous commodification of electrical energy. Simple pro-rata division of a wind farm's output does not

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provide discrimination between claims: fluctuations in the total power output of the farm will be reflected in each associated token, which may limit the ability to use such forward-bought electricity to offset the energy costs of responsive demands. It is also arguable that a tranching structure such as this provides consumers with a more tangible sense of association with a specific renewable generator, as this scheme can put them 'first in the queue' for electrical power flowing from an identifiable wind turbine.

Section II presents a simple marketplace simulation framework. Section III describes the data used in the test platform and the smart contract pricing. In Section IV, the results are presented and discussed. Section V concludes the paper.

II. Methodology

A. Representative market framework

1) Assumptions: Firstly, it is assumed that generators and consumers are equipped with blockchain-aware smart electricity meters, as in [18] (the feasability and implementation details of such supportive infrastructure is outside this paper's narrow scope.) Each consumer's meter can be 'credited' with blockchain tokens that embody a claim on a portion of the future power output of a particular generator. (How this real-time production data may be credibly oraclised [22] is likewise beyond the present scope.) These *ForDelToks* blockchain tokens could be freely and anonymously traded between actors, perhaps using decentralised exhanges [23].

In each time period, each consumer's meter queries a smart contract to infer how much of its consumption is offset by the real-time output of the *ForDelToks* it holds. Consumption in excess of this level must be paid for at a fixed pay-as-you-go rate [18], perhaps also using a blockchain payment system.

2) Market principles: If the 'output' of a *ForDelTok* exceeds a consumer's instantaneous consumption, the surplus provides no benefit to the consumer: a principle of *use it or lose it*. Each *ForDelTok* is valid for a particular timespan and embeds particular rules for how the generator's power output will be dispersed amongst *ForDelTok* holders. As a blockchain token, each *ForDelTok* could be freely traded without restrictions. However, the simple market model presented here only considers first-party trades between generators and consumers: third-party and derivative markets are beyond the scope of the present work, although they are fully facilitated within the blockchain paradigm.

B. ForDelTok Allocation model

This section describes an optimisation model that identifies equilibrium conditions for an idealised marketplace which has some resemblance to a *ForDelTok* exchange platform. It is important to note that blockchain decentralised exchanges are flexible and unrestricted: they are not operated according to strict trading rules nor cleared by any central party. The present optimisation model is only proposed to identify the types of equilibrium that such a vibrant and open marketplace might tend to converge towards. This will facilitate a discussion of the potential benefits of such schemes: this allocation model *is not* proposed as a set of rules for operating a blockchain marketplace, but only as an illustrative simulation.

The *ForDelTok* market is simulated using a cost minimisation allocation model whereby the *ForDelToks* contracts are allocated from the generators to the consumers so as minimise the sum of consumer costs. A cost minimisation approach should find a similar equilibrium to that acheived in an efficient marketplace [24] where generators and consumers can transact with each other bilaterally without regulation.

The following nomenclature is used: lower-case Roman letters indicate indices or primal variables while upper-case Roman letters represent parameters.

The model minimises total consumer cost over T timesteps by determining the energy ($con_{i,k,t}$) consumer group k gets from contract i at time t in addition to the pay-as-you-go energy they buy ($n_{k,t}$). A binary variable is used to indicate if consumer group k holds contract i ($d_{i,k} = 1$) or not ($d_{i,k} = 0$). Consumers have two types of demand: un-shift-able demand ($DEM_{k,t}$), which must be consumed at time t, and shift-able demand ($dr_{k,t}$), which must also be consumed but the time at which this happens is optimally determined by the model. The binary variable $b_{k,l}$ represents when consumer k begin consuming it's shift-able demand; $b_{k,l} = 1$ if at time l and $b_{k,l} = 0$ if not. The optimisation problem is:

$$\min_{\substack{n_{k,t},dr_{k,t}\\ d_{i,k},b_{k,l}}} \sum_{k,t} \overline{P} \times n_{k,t} + \sum_{i,t,k} \underline{P} \times CON_{i,t} \times d_{i,k} \quad (1)$$

subject to:

$$DEM_{k,t} + dr_{k,t} = n_{k,t} + \sum_{i} con_{i,k,t}, \ \forall k, t, \quad (2)$$

$$con_{i,k,t} \leq \overline{CON}_{i,t} \times d_{i,k}, \ \forall i, k, t, \quad (3)$$

$$\sum_{k} d_{i,k} \leq 1, \ \forall i, \quad (4)$$

$$dr_{k,t} = \sum_{l} E_{k,l,t} \times b_{k,l}, \ \forall k, t, \quad (5)$$

$$\sum_{l} b_{k,l} = 1, \ \forall k, \quad (6)$$

$$dr_{k,t} \leq \overline{DR}_{k,t}, \ \forall k, t, \quad (7)$$

where $\overline{P}$ represents the pay-as-you-go price consumers pay to a liquidity provider. The price $\underline{P}$ represents the price generators would receive for their energy from the liquidity provider and thus represents the minimum price they would be willing to sell to the consumers at. The total consumer costs in objective function (1) represent consumers' pay-as-you-go cost in addition to their *ForDelTok* costs. Note that consumers would have to pay just marginally more than the $\underline{P}$ floor price for each unit of energy in the *ForDelTok*, regardless of whether they use it: this is the lowest price a generator would theoretically accept. Constraint (2) ensures demand balances for each consumer at each timestep. Constraint (3) limits the amount of energy consumer group receives at time t from contract i. If contract energy available in timestep t is greater than consumer k's demand, then some of the contract will not be utilised. Constraint (4) ensures contract i can only be

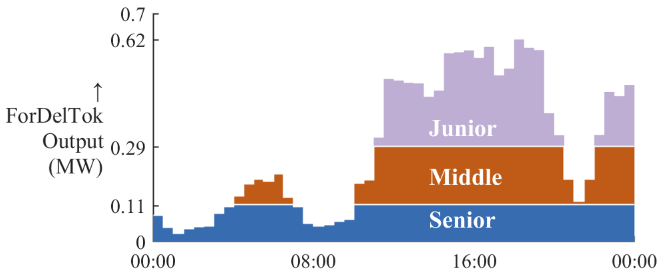

Fig. 1. An example of how the tranching scheme operates, showing the division of g1's output for day 2

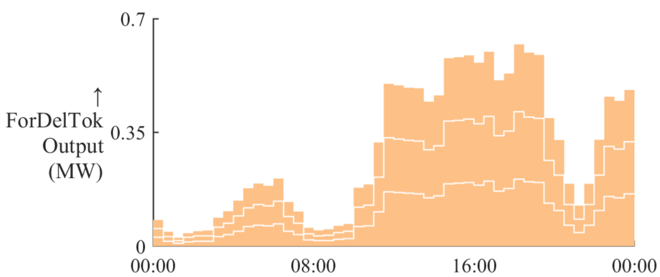

Fig. 2. An example of how the prorata scheme operates, showing the division of g1's output for day 2

given to, at most, one consumer. Constraint (5) determines the shift-able demand each consumer group consumes at time t where the parameter $E_{k,l,t}$ represents consumer group k's shift-able demand at time t if their begin consuming their shift-able demand at time l. Constraint (6) ensures each consumer group k must begin consuming its shift-able load at some point. Constraint (7) limits when consumer k can shift their demand to. The parameter $\overline{DR}_{k,t} = 0$ if consumer k cannot shift their demand to timestep t. Otherwise, $\overline{DR}_{k,t} = \infty$. These constraints ensure that once consumers begin consuming their shift-able demand, they must continue. This type of demand response corresponds to processes which run for a set period of time, such as the charging of a car or specific manufacturing activities.

Finally, all variables are also constrained to be non-negative.

III. Test Platform

A. Test data

The market simulation involves the application of the representative market framework to the Australian system on two typical summer days [25]–[27]. Wind contribution to seasonal peak demand is generally higher in summer than in winter in Australia based on [28]. Each daily profile consists of 48 half-hourly wind generation and consumer load of Australian Energy Market Operator. Due to the scope of this paper, a simplified yet representative framework for the wind generator-load dynamics is considered. Data regarding the output of three wind generators was taken from [29] to represent the future electrical power delivery underlying the *ForDelTok* contracts, as shown as sparklines in tables II and III. Five different load profiles where retrieved from [30] to mimic the real-time demand of consumer groups. These load profiles, after some demand response shifting, are shown in yellow in figure 3.

TABLE I. Demand response parameters

Load	Power (kW)	Duration (hours)	Earliest Start	Latest End
$k1$	59	$2\frac{1}{2}$	09:00	17:00
$k2$	170	3	09:00	17:00
$k3$	138	$3\frac{1}{2}$	10:00	18:30
$k4$	104	3	09:00	17:00
$k5$	51	3	09:00	19:30

The marketplace equilibrium problem is a Mixed Integer Linear Program and is solved using GAMS with an optimally gap of 0.0. Demand response parameters are as given in table I. Market-making price parameters were set at $\overline{P} = 25$ and $\underline{P} = 16$.

1) Construction of equal energy tranches: To partition the time series data into the equal-energy tranches an algorithm iterated through candidate power thresholds until each *ForDelTok* contained approximately one third of the total energy produced by each generator for each day. Examples of this tokenisation process are given in figures 1, which shows three *ForDelTok* representing **junior**, **middle**, and **senior** tranches of a particular wind farm's output. As a comparison, figure 2 shows the simple **pro rata** division of a wind farm's output.

B. Determining ForDelTok prices

The optimization model does not explicitly determine the specific price each consumer will pay the generator for each *ForDelTok* they purchase. If all the consumers were to behave completely rationally and seek the best price from the generators, the *ForDelTok* price would tend to £$\underline{P}$/kWh as the generators would compete amongst each other until that floor price was reached. Similarly, if there was not even one consumer willing to do this, generators could set the price at £$\overline{P}$/kWh so as to maximise their profits. When the *ForDelTok* price is £$\overline{P}$/kWh, consumers do not benefit from the *ForDelTok*s as they would pay the same as pay-as-you-go price. Similarly, if the *ForDelTok* price is £$\underline{P}$/kWh, generators would not benefit.

In reality, some consumers behave rationally and others do not [31] and thus it can be anticipated that the price of the *ForDelToks ForDelTok*s will lie between $\overline{P}$ and $\underline{P}$ and both consumer and generators may gain financially.

IV. Results

The raw data and scripts underlying these results are available at [32].

The market simulation was undertaken to verify whether the flexibility offered by peer-to-peer smart contracts on a blockchain could be exploited to coordinate and optimise wind generation-load dynamics in electricity networks. Tables II and III show the allocation of each *ForDelToks* contract i from every generator g to each consumer group k under the tranched and pro-rata systems during two typical summer days. The allocation process maximises the generator's revenue gain and the consumer's saving by assuming a floor *ForDelTok* price $\underline{P}$, at which generators may sell to the liquidity provider, and

TABLE II. *ForDelTok* ALLOCATION: DAY 1

ForDelTok	Profile Sparkline	Sold by / to	Energy content (kWhr)	Used energy (kWhr)	Max generator revenue gain	Max consumer saving
$i9$ Tr Junior		$g3 \longrightarrow k2$	3.51	3.38	£0.28	£0.30
$i8$ Tr Middle		$g3 \longrightarrow k3$	3.56	3.56	£0.32	£0.32
$i7$ Tr Senior		$g3 \longrightarrow k3$	3.54	3.54	£0.32	£0.32
$i6$ Tr Junior			2.63	0	£-0.42	£0
$i5$ Tr Middle		$g2 \longrightarrow k3$	2.65	2.65	£0.24	£0.24
$i4$ Tr Senior		$g2 \longrightarrow k4$	2.64	2.64	£0.24	£0.24
$i3$ Tr Junior			1.44	0	£-0.23	£0
$i2$ Tr Middle		$g1 \longrightarrow k2$	1.46	1.46	£0.13	£0.13
$i1$ Tr Senior		$g1 \longrightarrow k5$	1.47	1.23	£0.07	£0.11
					$\sum = £0.95$	$\sum = £1.66$
$i9$ Pro Rata		$g3 \longrightarrow k2$	3.54	3.46	£0.30	£0.31
$i8$ Pro Rata		$g3 \longrightarrow k2$	3.54	3.16	£0.22	£0.28
$i7$ Pro Rata		$g3 \longrightarrow k3$	3.54	3.42	£0.29	£0.31
$i6$ Pro Rata		$g2 \longrightarrow k4$	2.64	2.57	£0.22	£0.23
$i5$ Pro Rata		$g2 \longrightarrow k2$	2.64	2.56	£0.22	£0.23
$i4$ Pro Rata		$g2 \longrightarrow k3$	2.64	2.43	£0.19	£0.22
$i3$ Pro Rata		$g1 \longrightarrow k3$	1.46	1.41	£0.12	£0.13
$i2$ Pro Rata		$g1 \longrightarrow k1$	1.46	1.05	£0.03	£0.09
$i1$ Pro Rata		$g1 \longrightarrow k5$	1.46	1.14	£0.05	£0.10
					$\sum = £1.64$	$\sum = £1.91$

TABLE III. *ForDelTok* ALLOCATION: DAY 2

ForDelTok	Profile Sparkline	Sold by / to	Energy content (kWhr)	Used energy (kWhr)	Max generator revenue gain	Max consumer saving
$i9$ Tr Junior			6.35	0	£-1.02	£0
$i8$ Tr Middle		$g3 \longrightarrow k2$	6.43	6.06	£0.49	£0.55
$i7$ Tr Senior		$g3 \longrightarrow k3$	6.42	6.33	£0.56	£0.57
$i6$ Tr Junior			11.84	0	£-1.89	£0
$i5$ Tr Middle			11.89	0	£-1.90	£0
$i4$ Tr Senior			11.93	0	£-1.91	£0
$i3$ Tr Junior			4.68	0	£-0.75	£0
$i2$ Tr Middle			4.74	0	£-0.76	£0
$i1$ Tr Senior		$g1 \longrightarrow k4$	4.76	4.60	£0.39	£0.41
					$\sum = £-6.79$	$\sum = £1.53$
$i9$ Pro Rata		$g3 \longrightarrow k2$	6.40	6.22	£0.53	£0.56
$i8$ Pro Rata			6.40	0	£-1.02	£0
$i7$ Pro Rata		$g3 \longrightarrow k3$	6.40	5.83	£0.43	£0.52
$i6$ Pro Rata			11.88	0	£-1.90	£0
$i5$ Pro Rata			11.88	0	£-1.90	£0
$i4$ Pro Rata			11.88	0	£-1.90	£0
$i3$ Pro Rata		$g1 \longrightarrow k4$	4.73	4.16	£0.28	£0.37
$i2$ Pro Rata			4.73	0	£-0.76	£0
$i1$ Pro Rata			4.73	0	£-0.76	£0
					$\sum = £-6.99$	$\sum = £1.46$

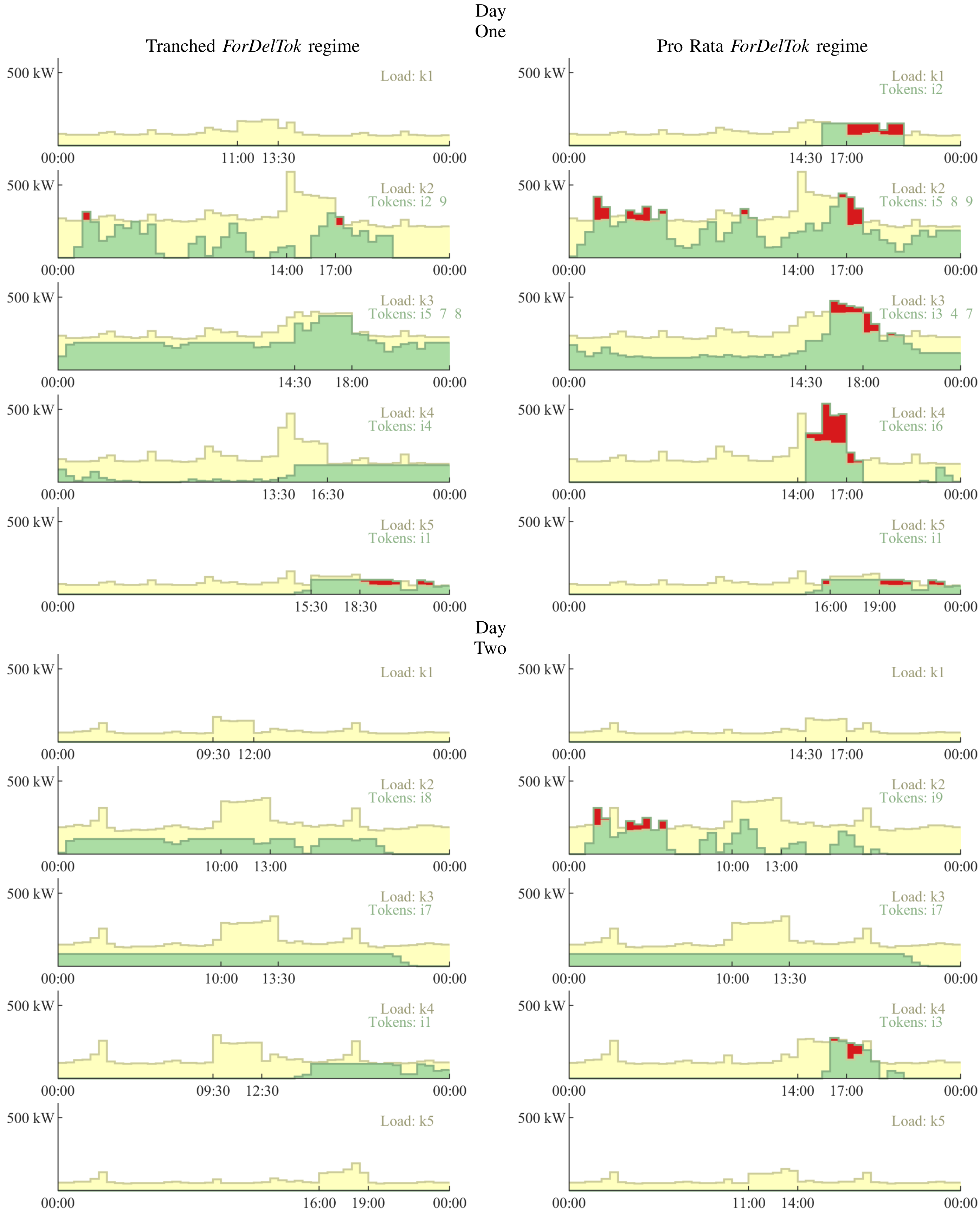

Fig. 3. This table shows each consumers final daily consumption in yellow, with the portion of this supplied by the aggregate of their purchased *ForDelToks* contracts shown in green. The portion of energy purchased but not consumed is shown in **red**. The tickmarks on the horizontal axis indicate the start and end times for demand response activation

TABLE IV. NET LOAD SUMMARY

	Peak-to-Valley (kW)	Relative Peak Reduction (%)	*ForDelTok* Utilisation (%)
Day 1			
Tranched *ForDelTok* regime	1310	18%	98%
Pro Rata *ForDelTok* regime	1359	18%	88%
Day 2			
Tranched *ForDelTok* regime	815	19%	97%
Pro Rata *ForDelTok* regime	874	8%	93%

TABLE V. MARKET OUT TURN SUMMARY

	Tranched *ForDelTok* regime	Pro Rata *ForDelTok* regime	Pay As You Go regime
Day 1			
Max gen revenue gain £	0.95	1.64	0
Max gen revenue gain %	46%	79%	-
Max consumer cost saving £	1.66	1.91	0
Max consumer savings %	81%	93%	-
Mean token energy utilisation %	81%	92%	NA
Day 2			
Max gen revenue gain £	-6.79	-6.99	0
Max gen revenue gain %	−109%	−113%	-
Max consumer cost saving £	1.53	1.46	0
Max consumer savings %	25%	23%	-
Mean token energy utilisation %	25%	23%	NA

a ceiling $\overline{P}$, set by the price at which consumers can buy electricity from the liquidity provider.

The energy content of the *ForDelToks* contracts under the tranched and the pro-rata allocation regimes is equivalent: the same delivery of electrical energy is available in each case. Notably, though, the real-time demand of each consumer actually satisfied by the *ForDelToks* contracts differs between the two differentiation regimes. Specifically, the energy utilisation of senior tranches ($i1$, $i4$, $i7$) is maximised in the tranched system compared to the pro-rata regime. This is mostly evident in Day 1 (Table II), when consumer groups $k3$, $k4$ and $k5$ benefit from a higher energy use in the tranched system, particularly during the middle of the day (9.00 a.m. to 9.00 p.m.), that is when the availability of flexible load is higher, as shown by the sparklines.

The dynamics implied in Tables II and III are documented in Figure 3, which depicts the consumers final daily consumption (**yellow**) and the portion of this consumption satisfied through *ForDelToks* contracts (**green**) over the 2 days in the different regimes. Overall, the figure shows a more efficient implementation of energy trading through a tranched system compared to a pro-rata system: note how the flat green power delivery blocks on the left side result in less unutilised *ForDelToks* entitlement (**red**). The uninterrupted blocks of constant power over prolonged periods are more frequent when the discriminatory regime is on place, such as in Day 1 for consumer groups $k3$, $k4$ and $k5$, and in Day 2 for consumer groups $k2$, $k3$ and $k4$. Furthermore, the tranched system maximises the allocation of the energy flow across consumers thus optimising their shiftable load and reducing the amount of energy that is purchased but not utilised by the consumers (red areas in the figure). Consequently, the tranched *ForDelToks* regime would better accommodate the efficient activation of demand response with intertemporal constraints or cycling costs, such as an energy storage system, including plug-in electric vehicles. Therefore, results in this paper add to previous research focusing on the application of blockchain techniques to peer-to-peer energy trading and automated demand response in decentralised system [33], [10].

A. *Effect on load profile shape*

The tableau in figure 3 shows how demand response activiations vary between the two regimes (start and finish times for these are shown as tick marks on the horizontal axis) Along the left hand side, it can be seen where these activations are optimally shifted to fit inside times when a particular consumer is well-supplied by *ForDelTok* power: for instance, load $k3$ on day one. The general flatness of power delivery profiles to the left is quite noticable, with power delivery on the right fluctuating in a way that causes more spillage of unused tokenised power.

Interestingly, in this study the optimisation of demand responses would be achieved through the specific structure of the *ForDelToks* contract and delivery system, rather than by time-of-use prices, thus limiting possible new demand peaks caused by the same low price periods [25], [34]. Table IV reports the peak-to-valley power shift in the two regimes, which is defined as the difference between the maximum and minimum total load in Figure 3, net of the *ForDelTok* utilisation. Both in Day 1 and Day 2, the tranched regime limits the net load peak-to-valley (1310 kW and 815 kW in Day 1 and Day 2 respectively) compared to the pro-rata regime (1359 kW and 874 kW). This outcome has implications for the interaction between concentrated shifts of reschedulable demand and power grid stability [35] [36]. The effect of the discriminatory system in limiting the creation of new demand peaks can be also inferred from the relative peak reduction in Table IV, which is obtained from the ratio of the maximum total load to the maximum load net of the used *ForDelTok*s, as depicted in Figure 3. Overall, the tranched *ForDelToks* regime allows for a somewhat higher peak reduction (18% and 19% in Day 1 and Day 2, respectively) when compared to the peak reduction achievable through a pro-rata regime (18% and 9%). This evidence implies a more efficient allocation of the power delivery *ForDelTok*s in the tranched regime, resulting in an utilisation of the activated *ForDelTok*s of 98% and 97% in Day 1 and Day 2 respectively, relative to 88% and 93% of the pro-rata regime.

B. *Market out-turn analysis*

Results in this paper contribute to address the advantages of blockchain in facilitating the participation of demand-side (consumers) in energy system management [10] [37]. Furthermore, these results suggest how, in energy markets, the token economy can encourage energy trading in the future low-carbon electrical industry [38]. Table V summarises the market out-turns from the simulation exercise. In Day 1, the utilisation of all available *ForDelToks* contracts is above 80% under both the regimes. Whilst the pro-rata regime maximises total generators' revenues and consumers' saving, it can hamper an efficient activation of demand responses, as implied by the results in Table IV. Yet, when the total amount of *ForDelToks* contracts used is not greater than 25%, as in Day 2, the tranched system appears to be more suitable to curb wind generators' losses. With 75% of wind power plant costs being upfront capital expenditure with usually high level of debt [39], stable revenues are crucial for generators. Compared to a pro-rata system, a discriminatory allocation system improves the profit effectiveness of wind farms against wind unpredictability, thus offering generators a risk-hedging instrument other than modifying offers in short-term markets [40]. This outcome is particularly interesting when considering the increasing penetration of renewable energy and the progressive phase-out of renewable subsidies, which can affect the level of future investment in renewable generation [11]. Also, whilst net metering and feed-in tariffs are fixed rates, which actually decouple generators and consumers from price signals that might otherwise direct investment and consumption decisions [41], blockchain-enabled peer-to-peer contracts promote a decentralised price discovery process for electricity trading [42] [43].

While this study does not account for the impact of uncertain real-time prices on purchasing decisions in the forward market [44], *ForDelToks* contracts are bilaterally traded at any price agreed upon generators and consumer groups, regardless of the market prices. Since the contract price lies between the minimum price at which generators can sell electricity in the wholesale market, $\underline{P}$, , and the maximum price at which consumers can buy electricity from the market maker, $\overline{P}$, any price uncertainty is absorbed and the effects of the real-time price distribution in a peer-to-peer forward trading setting become negligible. This implies that blockchain-based peer-to-peer *ForDelToks* forward contracts are less vulnerable to real-time price volatility and would represent an effective option for price volatility risk management [6], [7], [19], mostly for generators. Results in this paper show that generator's risk management can be optimised by a discriminatory energy allocation system, such as the tranched system. Table V shows the maximum generators' revenue gain and the maximum consumers' saving in Day 2, which is characterised by excess of supply (i.e. low energy use compared to the *ForDelToks* contracts energy content). Overall, negative revenues are minimised with a tranched system, while consumers' saving is maximised, along with demand responses (consumer groups $k3$ and $k4$). Therefore, as far as futures markets lead in the real-time price discovery process [45], the proposed tranched system would represent a more efficient way not only to deliver price information on energy costs to consumers, but also to facilitate effective risk management and appropriate investments in renewable generation capacity. In such a context, the proposed tranching structure contributes to the recent research blockchain-enabled smart contracts design in distributed peer-to-peer energy systems [21]. Furthermore, while at the present, research mainly focuses on future applications of blockchain-enabled distributed energy resources, [21], [46], [47], the blockchain-enabled smart contract design proposed in this study is for the trading of power contracts for future delivery, thus representing a further application of smart contract technology in distributed energy management.

C. Limitations

The analysis does not allow for market uncertainty or market power in the trading relationship between renewable generators and consumers [48] [44] [4]. Scalability and costs are further issues when considering the properties of decentralisation and supply security [47], which are not considered in this study. These aspects are left for future research.

V. Conclusions

A peer-to-peer platform has been proposed for the forward trading of tokenised power delivery contracts, where blockchain technology is integrated as a cyber-layer in a decentralised system and used for electricity trading. Results show that these cyber-physical forward contracts can yield better outcomes for consumers while maximising wind generators revenues. The contribution of this study is to show that a discriminatory blockchain-based forward trading system, such as the proposed tranched system, can provide a more effective incentive for demand response and smart management of energy consumption compared to a more naive pro-rata regime. Results also show the superiority of such a discriminatory system in facilitating renewable generators' risk management and for consumer-oriented marketplaces to support decentralised renewable generation. Therefore, blockchain technology and the proposed cyber-physical forward trading system would support the development and operation of decentralised energy systems and smart grids. While the discriminatory approach in this paper can enable more efficient and flexible decentralised markets, some limitations to the undertaken analysis should be acknowledged.

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