Blockchain Electricity Trading Under Demurrage

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***Abstract*—This letter proposes a novel *demurrage* mechanism for blockchain electricity marketplaces, whereby the redemptive value of energy-backed tokens declines with time. This mechanism is intended to reward organic price-responsive load shifting by incentivising the consumption of electricity when it is locally abundant. To demonstrate how such a demurrage mechanism might function in practice, this letter describes a mixed complementarity model of a notional token marketplace. These market simulations indicate that, in equilibrium and with rational actors, the demurrage mechanism creates price signals that temporally align the production and consumption of electricity.**

I. Introduction

MODERN blockchain technologies, which are secured by cryptographic proofs, facilitate the transfer of cash-like digital tokens in a trustless and immutable manner [1]. Remote parties can now undertake financial transactions without the need for mutual trust nor central intermediaries. Can the blockchain therefore enable a peer-to-peer marketplace for electrical energy?

Tentative proposals already exist for the deployment of blockchain technology in such roles [2], [3]. A typical scheme might be structured as follows: each consumer has a blockchain meter which expunges a token whenever a unit of electricity is consumed, similar to a coin prepayment meter. Likewise, these tokens are created when generators export energy to the network. To keep their meters in credit, consumers may freely source tokens from generators: in this way peer-to-peer trading can be enabled using an existing physical distribution network. The present letter will articulate the benefits of implementing token demurrage within such a scheme.

There are various motivations for this kind of time-sensitive and directly transactive paradigm. Firstly, a well-structured blockchain energy marketplace should be able to foster price signals that shift electricity consumption to times when it is locally abundant: such responsive demand has well-documented benefits [4]. Secondly, removing intermediaries allows renewable energy producers to form meaningful relationships with their consumers and thereby brand their energy [5], perhaps facilitating price premiums.

Newer blockchains [6] provide Turing-complete scripting capabilities which allow *smart contracts* to be executed between remote actors in a fully decentralized, provably-fair manner. Early proposals exist for using such smart contracts to co-ordinate electricity trading at the consumer level [7]. The present work proposes the use of smart contracts to impose demurrage on tokenised electrical energy [8], whereby the redemptive value of the energy-backed token declines with time. This demurrage mechanism is proposed to disincentivise token hoarding and should foster price signals that shift electricity consumption to time periods when local generation is most plentiful.

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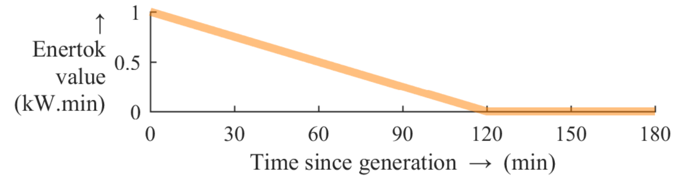


Fig. 1. Demurrage: an Enertok's redemptive value declines after it is generated

II. Methodology

This section describes a framework for simulating the price dynamics of organic token trading activity between generators and consumers. Although these trades will occur in an ad-hoc, expedient and unregulated fashion, it is possible to calculate the equilibrium prices such a liquid marketplace should achieve under certain rationality assumptions. The presented formulation is in no way proposed as a set of centralised rules to regulate peer-to-peer electricity trading. These simulations are undertaken solely to articulate how a demurrage mechanism would affect the equilibrium price reached on a bilateral exchange for blockchain tokens. Decentralised exchanges [9] are already operating which deploy smart contracts to match buyers and sellers of blockchain tokens without central intermediation. Such an exchange can facilitate transactions whereby generators directly sell their energy-backed tokens to consumers in exchange for a stablecoin [10] pegged to a fiat currency. To the extent that such a marketplace is liquid, it should attain an efficient equilibrium where prices reflect underlying utilities.

1) Assumptions: The assumptions underpinning the exemplary marketplace simulations are as follows: consumers may source *Enertoks* either directly from local generators at the prevailing spot price, or from a 'last-resort' liquidity provider at a fixed ceiling price. The liquidity provider might be the local distribution system operator that physically connects the community to the wider grid, who could be mandated by a regulator to facilitate transactive electricity schemes. Each generator can decide when to sell each Enertok they produce, and each consumer decides when to buy, and when to consume, each Enertok. It is implicitly assumed that actors have intelligent software agents participating in the marketplace on their behalf, as in [3], and that these agents can modulate consumers' loads to provide some demand response. At the moment of creation, each Enertok can be redeemed for a specific quantum of electrical energy, and this redemptive value declines according to the linear demurrage function (as shown in fig. 1).

2) Simulation formulation: The equilibrium marketplace dynamics are simulated using a *Mixed Complementarity Problem* (MCP) [11]. The MCP represents a transactive markeplace for tokenised electricity and solves the optimisation problems of K consumers and G generators simultaneously and in equilibrium. The $K+G$ optimisation problems are connected through *market clearing conditions*, which are solved as part of the MCP. As the problem does not involve market power considerations, nor does it constrain any primal and dual variables together, it may be solved using a single objective cost minimisation problem [12]. Thus, the obtained solution should correspond to an efficient equilibrium for an Enertok marketplace. We simulate the marketplace price dynamics at an arbitrary granularity.

The following nomenclature is used: lower-case Roman letters indicate indices or primal variables, upper-case Roman letters represent parameters, while Greek letters indicate prices or dual variables. Each problem is optimised over T timesteps. All primal decision variables for each player are constrained to be non-negative.

3) Consumer k's problem: Consumer k seeks to minimise the cost of meeting their demand by choosing the amount of open-market Enertoks ($e^{\text{bought}}_{k,t,\tau}$) to be bought at time t and consumed at time τ. They also choose the amount of Enertoks ($n_{k,t}$) to buy at each timestep from a liquidity provider at the static pay-as-you-go price, P, for immediate consumption. Further, consumer k may utilise demand response: the variables $dr^{\text{up}}_{k,t}$ and $dr^{\text{down}}_{k,t}$ represent the amount by which they increase or decrease their load in each timestep, respectively. Consumer k's optimisation problem is:

$$\min_{\substack{e^{\text{bought}}_{k,t,\tau}, n_{k,t}\\ dr^{\text{up}}_{k,t}, dr^{\text{down}}_{k,t}}} \quad \sum_{t=1}^{T} \big(\pi_t \times (\sum_{\tau=1}^{T} e^{\text{bought}}_{k,t,\tau}) + P \times n_{k,t}\big), \qquad (1)$$

subject to:

$$n_{k,t} + \sum_{\tau=1}^{T} F^{\text{con}}_{\tau,t} e^{\text{bought}}_{k,\tau,t} = DEM_{k,t} + dr^{\text{up}}_{k,t} - dr^{\text{down}}_{k,t},\ \forall t, \quad (2)$$

$$\sum_{t=1}^{T} dr^{\text{up}}_{k,t} - dr^{\text{down}}_{k,t} \quad = \quad 0,\ \forall t, \qquad (3)$$

$$dr^{\text{down}}_{k,t}, dr^{\text{up}}_{k,t} \quad \leq \quad DR^{MAX}_{k}, \quad \forall t, \qquad (4)$$

where π_t is the equilibrium Enertok price at t. This price is exogenous to the consumer k's problem but is a variable of the overall MCP. The parameter $DEM_{k,t}$ represents consumer k's reference load, i.e., their load in the absence of any load shifting. The demurrage scalar parameter takes the form $F^{\text{con}}_{\tau,t} = 1 - \frac{t-\tau}{F^{time}}$ if $(t - F^{time}) < \tau \leq t$ and zero otherwise. It describes how the redemptive value of an Enertok decreases linearly, reaching zero in the F^{time} timesteps after it has been generated (recall fig. 1). Likewise, consumers may not consume an Enertok before it is bought as $F_{\tau,t}$ is also zero for all timesteps before it is transacted. By reducing the ability of older Enertoks to offset consumption within constraint (2), this demurrage mechanism punishes the hoarding of Enertoks and incentivises rational consumers to shift their consumption to time periods when Enertoks are abundant. Constraint (2) also ensures that the amount of electricity consumed in each timestep matches the prevailing demand, while constraint (3) ensures that, in energy terms, demand response upshifts (dr^{up}) and downshifts (dr^{down}) must balance over time. Constraint (4) limits the permissible increase or decrease in load in each timestep.

4) Generator g's problem: Generator g seeks to maximise revenues by selling Enertoks ($e^{\text{sold}}_{g,t,l}$), delivered at time t, using electricity generated at time l. It is also affected by the demurrage function in that the transactive value an Enertok produced at time l decreases linearly until it is delivered at time t. Generator g's optimisation problem is:

$$\max_{e^{\text{sold}}_{g,t,l}} \ \sum_{t=1}^{T} \pi_t \times (\sum_{l=1}^{T} F^{\text{gen}}_{t,l} e^{\text{sold}}_{g,t,l}), \qquad (5)$$

subject to

$$\sum_{l=1}^{T} e^{\text{sold}}_{g,l,t} \quad \leq \quad CAP_{g,t},\ \forall t, \qquad (6)$$

where $F^{\text{gen}}_{t,l}$ is the transpose of $F^{\text{con}}_{\tau,t}$. The maximum output capacity at time t is $CAP_{g,t}$. As this varies with time, it is suitable for modelling renewable energy sources.

5) Market clearing conditions: The optimisation problems of k and g are connected using the following market clearing conditions:

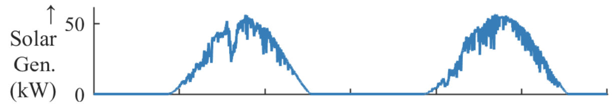
$$\sum_{k=1}^{K}\sum_{\tau=1}^{T} e^{\text{bought}}_{k,t,\tau} \quad = \quad \sum_{g=1}^{G}\sum_{l=1}^{T} F^{\text{gen}}_{t,l} e^{\text{sold}}_{g,t,l},\ \forall t,\ (\pi_t), \qquad (7)$$

which state that, for each timestep, the amount of Enertoks bought must equal the amount sold. The Enertok equilibrium price, π_t, is the Lagrange multiplier/marginal price associated with conditions (7). As it is the price that consumers and generators transact Enertoks at, it is calculated by the MCP via the Karush-Kuhn-Tucker (KKT) conditions of the different players.

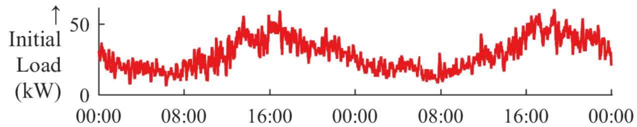
The MCP consists of the KKT conditions from each of the optimsiation problems in addition to conditions (7). As each optimisation is linear, and hence convex, these conditions are both necessary and sufficient for optimality. Thus, the solution provided by the MCP is a Nash equilibrium [13]. However, there may be multiple Nash-equilibria as any solution provided by the MCP may be non-unique.

III. Results

1) Test platform: A local renewable energy marketplace, composed of thirteen households and eleven small-scale photovoltaic generators, was created using two days' worth of data from the Pecan Street repository [14]. Aggregate reference demand ($\sum_k DEM_{k,t}$) and generation ($\sum_g CAP_{g,t}$) profiles over the test period are shown in Fig. 2. The liquidity provider sells Enertoks at $P = 0.25¢$, consistent with a price of €0.16 for a 1 kWh unit of electricity. F^{time} is set to 120 minutes.

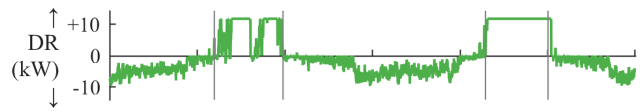


(a) the generation output capacity: $\sum_g CAP_{g,t}$

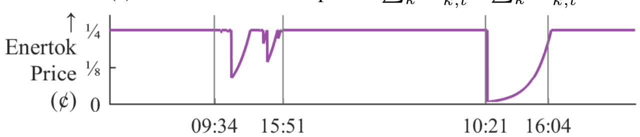


(b) the reference load: $\sum_k DEM_{k,t}$

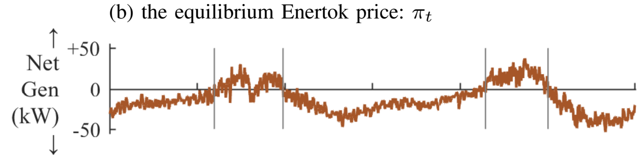
Fig. 2. The input parameter values over the two test days



(a) the total demand response: $\sum_k dr^{\text{up}}_{k,t}$ - $\sum_k dr^{\text{down}}_{k,t}$



(b) the equilibrium Enertok price: π_t



(c) the net generation: $\sum_g CAP_{g,t} - \sum_k DEM_{k,t}$

Fig. 3. The market out-turns shown in relation to the net generation

DR_k^{MAX} is set to 10% of each generator's maximum reference demand over the period. The simulation results and scripts are available at [15].

2) Simulated market dynamics: The ensemble in Fig. 3 portrays the market out-turns over the two test days. The generation ramps up to a significant output during daylight hours, and this creates a net surplus for several hours each day, as delineated in Fig. 3 (c). These periods of abundant local energy depress Enertok prices as in Fig. 3 (b), and invoke an uptick in the use of demand response, as in Fig. 3 (a). This shows that demurrage mechanism succeeds in temporally coupling the generation and consumption of electricity using price signals.

Note that even though there is a positive net generation from 09:34 on the first day, the Enertok price doesn't start to decrease until some minutes after this point, when consumers fully ramp up their demand response up to its maximum DR_k^{MAX}: this is because the consumers have the benefit of foresight, and can optimally wait for times of maximum abundance. The second day is more productive, with a more sustained period of net generation, and this results in very cheap Enertok prices and pronounced usage of demand response.

IV. Conclusions

This letter has shown that rational actors within a marketplace for time-sensitive tokenised electricity will provide a demand response to partially align their consumption with periods of abundant local generation.

Acknowledgements

The authors thank Dr. Hugo Gil for his role in work preceding the present letter.

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