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Towards a Distributed Autonomous Organisation for Financing, Governing and Disbursing Revenues of a Battery Energy Storage System

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***Abstract*—This paper presents a framework for a blockchain-based decentralised autonomous organisation that mediates the financing, governance, and revenue dispersal for a battery energy storage system fully controlled by remote token holders. In the proposed framework, the participants can buy a fractional share of an energy storage asset, embodied as a blockchain token, with corresponding rights and privileges enforced by smart contracts. The token holders continually vote to govern the battery's operation (charge/float/discharge); these votes are autonomously aggregated by the smart contract, which is also empowered to directly dispatch the battery's mode of operation by issuing physical control signals. Furthermore, the smart contract itself maintains a financial payment channel with the electricity market, transacting stable coins back and forth as it buys and sells energy from the spot market, per the token holders' consensus wishes. This paper presents a case study simulation of this radical conception of asset ownership and control, whereby token holders vote based on the real-time price of electricity, their particular electricity price forecast, and the current state of charge of the battery.**

***Keywords*—Battery energy storage, Blockchain, Crowd-financing, decentralised governance, Distributed Autonomous Organisation.**

I. INTRODUCTION

Many countries worldwide are undergoing the energy transition as we move from large, centralised fossil fuel power systems to future power systems powered by renewable energy generation and storage resources. One of the most important integration to modern power systems is battery energy storage installations [1]. There are two major applications of battery energy storage systems namely *front-of-the-meter* and *behind-the-meter* applications. The advantages of battery energy storage systems in front-of-the-meter applications are to enhance the grid stability [2], manage power flows, reduce transportation costs, avoid network congestion, and defer the grid reinforcement [3]. The advantages of battery energy storage in behind-the-meter applications are a backup power source during natural disasters, effectively balancing the local demand & generation, reducing electricity bills, and maximising revenues. The network operators use battery energy storage to maximise the revenue from frequency control [4], energy arbitrage [5] and from various ancillary services, wholesale, and balancing markets [6]–[8].

The focus of this paper is on the ability of battery energy storage to make profits by arbitraging energy; buying at times when electricity is cheap, and discharging when the price is high. The novelty of this paper is in presenting a framework by which such a business function can be radically decentralised and democratised, whereby a smart contract, rather than a traditional legal entity, is the locus of interaction between electricity markets, investors, and the physical battery itself. Financing and governing battery energy storage systems have become an arduous process for traditional finance sources because of high costs [9]. Although Li-Ion battery costs are declining, there are not always proper incentives, and high prices are still considered as primary reasons for not many battery energy storage investments [10]. New innovative funding and managing options in energy storage assets may provide new revenue streams to investors.

Since Satoshi Nakamoto's white paper proposing Bitcoin was published in 2008, blockchain applications have been generating much discussion in many industries where there is the possibility of disintermediating financial incumbents [11]. The introduction of next-generation blockchains with smart contracts capabilities creates new business models and applications [12]. Smart contracts can effectively execute the transactions based on predefined rules and conditions without any third-party's intervention [13]. Proposals for the application of blockchain technology in electrical industries are increasing, such as for peer-to-peer energy trading, integration of renewable generators & electric vehicles, crowd-financing for energy assets, etc.

The authors in [14] outline a structure for a blockchain-enabled special purpose vehicle for financing renewable generation assets. The sharing economy is one of the primary reasons for recent developments in crowdfunding platforms backed by blockchain technology [10]. Blockchain-enabled crowdfunding for small-scale residential energy storage systems was presented in [9], which compares traditional and crowd-financing options for residential-scale battery energy storage systems. The authors in [15] illustrated three conceptual tiers for categorising blockchain-driven disruption. The tier-1 is characterised by a narrow focus on tokenization and bilateral peer-to-peer energy trading. Simple energy transactions characterise tier-2, countenancing ideas such as smart contract derivatives and federated arrangements. Finally, tier-3 is the most speculative,

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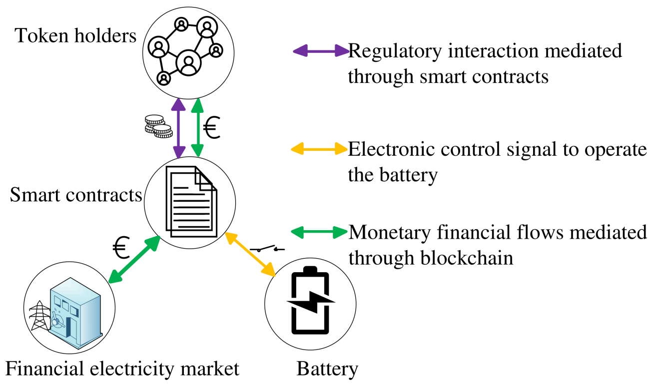

Fig. 1. Conceptual design structure of DAO.

considering such futurist ideas as decentralised autonomous organisations (DAOs), pure blockchain governance, and utilities replaced by anonymous blockchain collectives. The proposed framework in this paper focuses on ideas in tier-3 of this taxonomy.

With the development of blockchain technology, DAOs emerged in recent years. DAOs enable decentralised governance, ownership, consensus, and asset management without a central authority hierarchy. DAOs can establish transparent, secure, and immutable transactions through smart contracts and consensus protocols among distributed anonymous network users. In a DAO, token economic incentive mechanisms are used for governance and ownership [16]. The world's first DAO was launched in 2016 and raised crowdfunding worth US$150 million [17]. Today the top DAO tokens market capitalisation is more than US$ 13 billion with a trading volume of more than US$ 2 billion per day [18].

The smart contract-based ecosystem enables autonomous operations to dis-intermediate the current financial transactions in the electricity markets. If an energy market operator chooses to pay payments to all the stakeholders through blockchain-enabled platforms, that facilitates the futuristic DAO frameworks to operate/manage battery energy storage systems to generate new revenue streams for its stakeholders autonomously. Towards this aim, a battery energy storage system is considered for crowd financing, governance, and revenue sharing to decentralised token holders. As per the author's knowledge, the study of adopting blockchain technology to govern the operation of battery energy storage systems by decentralised shareholders is unaddressed in the literature.

II. Proposed Methodology

A. *Smart contract conceptual design*

In this proposed framework, financing, governance, and revenue sharing of battery energy storage systems are mediated autonomously through interconnected smart contracts. Interconnected smart contracts residing on a blockchain network form a DAO and execute operations autonomously based on predefined rules. Governing the energy storage system via a DAO enables decentralised control over the physical mode of operation of the battery energy storage system. As the DAO also interacts with the financial energy markets, buying and selling electricity as the battery charges and discharges, it inherently has custody of the relevant cash flows, and can therefore autonomously arrange onward disbursal of arbitrage profits to the token holders.

The conceptual design structure of the proposed DAO framework for financing, governing, and disbursing revenues of a battery energy storage system is shown in Fig. 1. The smart contracts in this paper are structured at the level of pseudo-algorithms. In this framework, it is assumed that three interconnected smart contracts (financing, governing, and revenue-sharing smart contracts) interact with the token holders, battery, and financial electricity markets, and each other. The financing smart contract interacts with investors to finance the battery energy storage system. The physical control signal to operate the battery is mediated through the governing smart contract. The revenue flows between financial electricity markets and token holders could be mediated through a revenue-sharing smart contract. The specific software implementation of such smart contracts is outside the scope of the present work, which focuses on articulating their potential functionality.

In this proposed framework, it is assumed that any investor connected to the blockchain network can buy fractional ownership of the energy storage asset and become a shareholder (token holder) through smart contract function calls. Smart contracts can utilise tokens to represent physical assets and provide certain rights to token holders. Because of the volatile nature of cryptocurrency, it is not suitable as a medium of exchange for transactions between shareholders in crowd financing. Nonetheless, stable coins pegged to fiat currencies are more suitable as a medium of exchange for transactions [14].

Once the crowdfunding target is reached, the smart contracts can grant the token holders the right to vote and share the revenues of the battery energy storage system. All the token holders get the right to vote for charging/floating/discharging the battery energy storage system considering the real-time utility price, their particular electricity price forecast, and the current state of charge of the battery. The governing smart contract determines the consensus mode of operation of the battery energy storage system considering all the proposed votes from token holders. In this framework, we assume that the future power system network will adopt blockchain-based cryptocurrency payment layers in energy trading. The revenue-sharing smart contract disburses the revenue generated from the battery energy storage system to all token holders based on a pro-rata share of their investment.

B. *Simulation methodology for illustrative case study*

To showcase the effectiveness of decentralised autonomous governance of the proposed framework, a case study was simulated by considering a battery energy storage system.

1) Voting mechanism: Each token holder will vote based on their own belief about how the battery storage system can maximise profits by effectively arbitraging energy. That is, each token holder will aim to charge the battery when electricity prices appear relatively low and to discharge at times of comparatively high prices.

This paper presents an arbitrary voting strategy for token holders based on their individually forecast price outlook. Different classical time-series forecasting methods are used in this case study to forecast the electricity price. At the beginning of each interval $t \in \mathcal{T} \triangleq [1, 2, ..., t, ..., T]$, every token holder $n \in \mathcal{N} \triangleq [1, 2, ..., n, ..., N]$ forecasts the electricity price profile (λ^n_{FP}) for the next T^+ interval horizon based on the historical electricity price profile using their own forecasting method. The real-time electricity price (λ^t_{RP}) from the utility and the current state of charge (SoC^{t-1}) of the battery are collected at the beginning of every interval t. The forecasted electricity price profile (λ^n_{FP}) is sorted in ascending order in order to identify low pricing intervals to charge and high pricing intervals to discharge the battery. Let t_s represents the low pricing intervals (storage duration) required to fully charge the battery. Then $\tilde{\lambda}^n_{FP}(1 : t_s)$ and $\tilde{\lambda}^n_{FP}(T^+ + 1 - t_s : T^+)$ represent the set of low and high electricity forecasted price period, respectively.

The main motive of token holders to vote is to maximise the revenue from the battery energy storage system. For example, token holders would not want to discharge the battery if they thought it would make more revenue by waiting to discharge later. So, the token holders prefer to vote for charging at periods they perceive to represent lower electricity prices. The vote to influence the mode of operation of the battery by token holder $n \in \mathcal{N}$ at the starting of an interval $t \in \mathcal{T}$ is defined in equation (1).

$$Vote^t_n = \begin{cases} 'C' & \text{for charging} \\ 'F' & \text{for floating} \\ 'D' & \text{for discharging} \end{cases} \quad (1)$$

A token holder proposes a vote $'C'$ when the current real-time price (λ^t_{RP}) belongs to low forecasted price set $\tilde{\lambda}^n_{FP}(1 : t_s)$; proposes a vote $'D'$ when the real-time price (λ^t_{RP}) belongs to high forecasted price set $\tilde{\lambda}^n_{FP}(T^+ + 1 - t_s : T^+)$ considering the battery discharging limits, and proposes a vote $'F'$ otherwise. The proposed arbitrary voting mechanism is presented mathematically in Algorithm 1. This voting strategy is not proposed to be optimal in any sense but merely serves as a credible decision-making procedure to translate idiosyncratic price forecasts into tangible votes.

2) Consensus decision-making procedure: The battery's real-time consensus mode of operation (charging/floating/discharging) is determined using a decision-making procedure after receiving proposed votes from the token holders, which is presented as a pseudo-algorithm in Algorithm 1. After collecting all the proposed votes from all the token holders, the consensus decision-making procedure determines the regime of operation of the battery based on the vote that occurs the highest number of times, which is defined in the equation as the statistical *mode* (2).

$$V^t_{con} = mode[Vote^t_1, Vote^t_2, ..., Vote^t_n, ..., Vote^t_N] \quad (2)$$

If the consensus regime of operation is $'C'$ then P^t_B = 1 MW, if consensus is $'D'$ then P^t_B = -1 MW, and if consensus is $'F'$ then P^t_B = 0 MW. The updated SoC of the battery based on the consensus mode of operation at the end of the interval t is defined in equation (3).

$$SoC^t = SoC^{t-1} + P^t_B \times (\eta / C_B) \quad \forall t \in \mathcal{T} \quad (3)$$

where P^t_B represents the charging/discharging power (MW) of the battery during an interval t. The η and C_B represent battery efficiency and nominal battery capacity (MWh) respectively.

Algorithm 1 Pseudo-algorithm for governing smart contract.

```
Input: $[SoC^{t-1}; \lambda^t_{RP}; \lambda^n_{FP}]$   $\forall t \in \mathcal{T}, n \in \mathcal{N}$
Output: $[SoC^t]$
  Initialisation : $[SoC_{min}; SoC_{max}; \eta; C_B; t \leftarrow 1]$
while $t \leq T$ do
    Voting mechanism:
    for $n = 1$ to $N$ do
        if $(SoC^{t-1} \leq SoC_{max}) \&\& (\lambda^t_{RP} \in \tilde{\lambda}^n_{FP}(1 : t_s))$ then
            $Vote^t_n = 'C'$;       // Vote for Charging
        else
            if $(SoC^{t-1} > SoC_{min}) \&\& (\lambda^t_{RP} \in \tilde{\lambda}^n_{FP}(T^+ + 1 - t_s : T^+))$ then
                $Vote^t_n = 'D'$;   // Vote for Discharging
            end if
        else
            $Vote^t_n = 'F'$;       // Vote for Floating
        end if
    end for
    Consensus decision-making procedure:
    $V^t_{con} = mode[Vote^t_1, Vote^t_2, ..., Vote^t_n, ..., Vote^t_N]$;
    if $V^t_{con} =' C'$ then
        $P^t_B = 1$;       // Battery Charging
    else
        if $V^t_{con} =' D'$ then
            $P^t_B = -1$;  // Battery Discharging
        end if
    else
        $P^t_B = 0$;       // Battery Floating
    end if
    $SoC^t = SoC^{t-1} + P_B \times (\eta / C_B)$;
    $t \leftarrow (t + 1)$;
end while
```

In this framework, the flow of revenue will be from the utility to token holders when the battery is discharging and from the token holders to the utility when the battery is charging. If the electricity price forecast is not accurate, then there will not be any considerable profit generation from the battery. The battery will generate significant revenue from the utility's energy arbitrage strategy if the forecast is accurate.

III. RESULTS AND DISCUSSIONS

A. Test platform

In this paper, we are simulating a 10 MWh battery energy storage system governed by five token holders as described in Table I, attempt to profit by implementing an energy arbitrage strategy over a sample week. The key characteristics of the battery energy storage system are given in Table II. We assume that this battery energy storage system participates in the electricity market whose price is taken from Energinet Group [19]. The MATLAB scripts utilised for simulating the case study and results can be found at Ref. [20].

B. Numerical Results

Every hour, the token holders propose voting to decide the energy storage system's mode of operation (charging/floating/discharging) based on real-time utility price, their

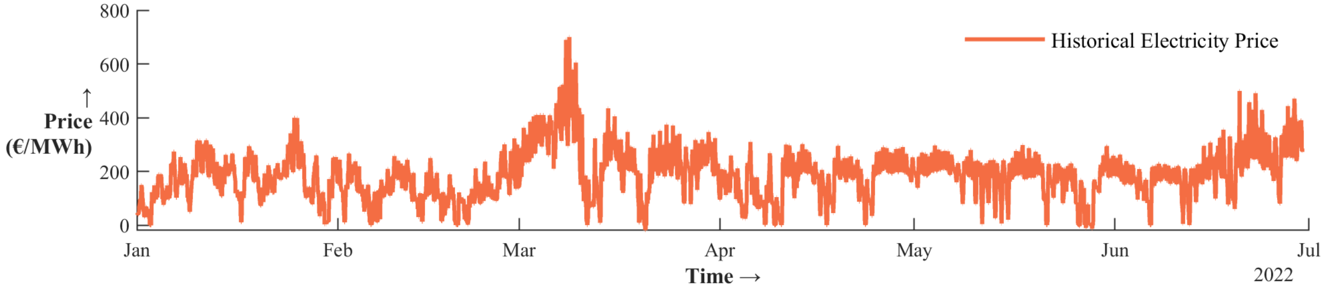

Fig. 2. Electricity price (01.01.2022 to 30.06.2022).

TABLE I.
Token holders with different forecasting methods and ownership

Token holder	Forecasting method	Fractional Ownership (%)
Token holder 1	Autoregression (AR)	20
Token holder 2	Moving Average (MA)	20
Token holder 3	Autoregressive Moving Average (AMA)	20
Token holder 4	Autoregressive Integrated Moving Average ($ARIMA$)	20
Token holder 5	Seasonal Autoregressive Integrated Moving-Average ($SARIMA$)	20

TABLE II.
Key Ideal characteristics of battery energy storage system

Characteristic	Symbol	Rating
Rated Energy Capacity	C_B	10 MWh
Rated Power Capacity	P_B	01 MW
Storage duration	t_s	10 hours
Initial State of Charge	SoC_{int}	10%
Minimum State of Charge	SoC_{min}	10%
Maximum State of Charge	SoC_{max}	90%
Battery Efficiency	η	100%
Battery self discharge	-	0%

electricity price forecast, and the current SoC of the battery. The electricity price is forecasted at the beginning of every hour for the next 24 hours using different classical time-series forecasting methods considering historical pricing information. The electricity price is taken from the Nord Pool spot market and is shown in Fig. 2. The electricity price profile from 01^{st} January 2022 to 19^{th} February 2022 (50 days) is considered as historical electricity prices and given as an input to the time-series forecasting methods. The electricity price forecast at 00:00 (hh:mm) 22^{nd} February 2022 using different time-series forecasting methods are compared with the real-time price profile and is shown in Fig.3.

The proposed DAO framework was simulated for one week (20-26 February 2022) to observe the revenue stream generated from the battery energy storage by participating in the energy arbitrage strategy. The decision-making procedure for three days (22-24 February 2022) is presented in Table III. It is observed from Table III that the consensus decision-making procedure is charging the battery at lower prices and discharging the battery at higher prices to generate revenue. The real-time price variation and SoC interpretation of the battery based on the consensus mode of operation of the battery are presented in Fig.4 and Fig.5 during a week (20-26 February 2022) respectively. The cash on hand (cumulative revenue) generation

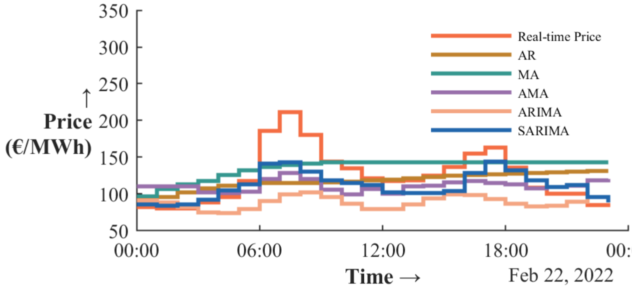

Fig. 3. Five different electricity price forecasts as at 00:00 22^{nd} February 2022. Each of these token holders may vote quite differently; do they individually believe that the price is likely to rise or fall? Is now a good time to charge or discharge the battery?

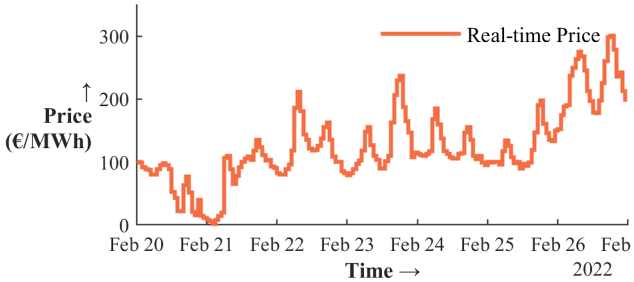

Fig. 4. Real-time price for a week in February 2022.

from the battery storage system for all the shareholders is presented in Fig.6. It is observed from Fig.6 that the proposed framework generated revenue of € 1867 from the battery energy storage system by participating in energy arbitrage mechanisms in one week. Finally, the revenues generated from the battery energy storage system in one week are disbursed to the token holders based on the pro-rata share of their initial investments.

IV. Conclusion

This paper has proposed a distributed autonomous organisation (DAO) framework for financing, governing, and distributing revenues of a battery energy storage system. The DAO enables decentralised control over the battery energy storage system through interconnected smart contracts. The proposed framework is structured in three types of smart contracts: the financing smart contract takes care of crowdfunding, the

TABLE III.
CONSENSUS OPERATION OF BATTERY IN THREE DAYS (22-24 FEBRUARY, 2022)

Time (t)	**Real-time price (€/MWh)**	**Current** SoC **(%)**	**Proposed votes based on prediction**					**Consensus mode of operation** (V_{con}^t)	**Updated** SoC **(%)**	**Revenue (€)**
			$Vote_1^t$	$Vote_2^t$	$Vote_3^t$	$Vote_4^t$	$Vote_5^t \mapsto$			
22-Feb-2022 00:00	82.14	90	F	F	F	F	F	F	90	0
22-Feb-2022 01:00	80.34	90	F	F	F	D	F	F	90	0
22-Feb-2022 02:00	79.90	90	F	F	F	F	F	F	90	0
22-Feb-2022 03:00	88.16	90	F	F	D	F	F	F	90	0
22-Feb-2022 04:00	95.36	90	F	F	D	F	D	F	90	0
22-Feb-2022 05:00	117.86	90	F	F	D	D	D	D	80	+117.86
22-Feb-2022 06:00	185.78	80	D	D	D	D	D	D	70	+185.78
22-Feb-2022 07:00	211.59	70	D	D	D	D	D	D	60	+211.59
22-Feb-2022 08:00	180.27	60	D	D	D	D	D	D	50	+180.27
22-Feb-2022 09:00	144.08	50	F	D	D	D	D	D	40	+144.08
22-Feb-2022 10:00	135.04	40	D	C	D	D	D	D	30	+135.04
22-Feb-2022 11:00	121.25	30	C	C	C	C	D	C	40	-121.25
22-Feb-2022 12:00	117.66	40	C	C	F	D	C	C	50	-117.66
22-Feb-2022 13:00	118.87	50	C	C	F	C	F	C	60	-118.87
22-Feb-2022 14:00	125.29	60	C	C	C	C	D	C	70	-125.29
22-Feb-2022 15:00	136.70	70	C	C	F	F	D	C	80	-136.70
22-Feb-2022 16:00	155.21	80	D	D	D	D	D	D	70	+155.21
22-Feb-2022 17:00	162.62	70	D	D	D	D	D	D	60	+162.62
22-Feb-2022 18:00	135.49	60	C	C	C	C	D	C	70	-135.49
22-Feb-2022 19:00	108.62	70	C	C	C	C	C	C	80	-108.60
22-Feb-2022 20:00	100.54	80	C	C	C	C	F	C	90	-100.54
22-Feb-2022 21:00	99.99	90	F	F	F	F	F	F	90	0
22-Feb-2022 22:00	85.08	90	F	F	F	F	F	F	90	0
22-Feb-2022 23:00	81.79	90	F	F	F	F	F	F	90	0
23-Feb-2022 00:00	78.96	90	F	F	F	F	F	F	90	0
23-Feb-2022 01:00	82.28	90	F	F	F	F	F	F	90	0
23-Feb-2022 02:00	88.34	90	F	F	F	F	F	F	90	0
23-Feb-2022 03:00	97.32	90	F	F	F	F	F	F	90	0
23-Feb-2022 04:00	101.70	90	F	F	F	F	F	F	90	0
23-Feb-2022 05:00	118.36	90	F	F	D	D	D	D	80	+118.36
23-Feb-2022 06:00	147.54	80	D	D	D	D	D	D	70	+147.54
23-Feb-2022 07:00	155.03	70	D	D	D	D	D	D	60	+155.03
23-Feb-2022 08:00	126.44	60	C	C	C	C	D	C	70	-126.44
23-Feb-2022 09:00	109.43	70	C	C	D	D	D	D	60	+109.43
23-Feb-2022 10:00	103.51	60	C	C	D	C	D	C	70	-103.51
23-Feb-2022 11:00	89.90	70	C	C	C	C	C	C	80	-89.90
23-Feb-2022 12:00	89.90	80	C	C	C	C	C	C	90	-89.90
23-Feb-2022 13:00	100.90	90	F	F	F	F	F	F	90	0
23-Feb-2022 14:00	109.49	90	F	F	D	F	F	F	90	0
23-Feb-2022 15:00	162.80	90	D	D	D	D	D	D	80	+162.80
23-Feb-2022 16:00	205.72	80	D	D	D	D	D	D	70	+205.72
23-Feb-2022 17:00	230	70	D	D	D	D	D	D	60	+230.00
23-Feb-2022 18:00	236.86	60	D	D	D	D	D	D	50	+236.86
23-Feb-2022 19:00	187.04	50	D	D	C	C	D	D	40	+187.04
23-Feb-2022 20:00	164.60	40	D	D	C	D	D	D	30	+164.60
23-Feb-2022 21:00	146.62	30	C	D	C	C	D	C	40	-146.62
23-Feb-2022 22:00	107.60	40	C	C	C	C	C	C	50	-107.60
23-Feb-2022 23:00	115.07	50	C	C	C	C	F	C	60	-115.07
24-Feb-2022 00:00	113.04	60	C	C	C	C	C	C	70	-113.04
24-Feb-2022 01:00	110.33	70	C	C	C	C	C	C	80	-110.33
24-Feb-2022 02:00	109.29	80	C	C	C	C	C	C	90	-109.29
24-Feb-2022 03:00	112.36	90	F	F	F	F	F	F	90	0
24-Feb-2022 04:00	116.77	90	F	F	F	D	F	F	90	0
24-Feb-2022 05:00	168.50	90	D	D	D	D	D	D	80	+168.50
24-Feb-2022 06:00	184.77	80	D	D	D	D	D	D	70	+184.77
24-Feb-2022 07:00	160.00	70	D	D	F	C	D	D	60	+160.00
24-Feb-2022 08:00	137.34	60	C	C	D	C	D	C	70	-137.34
24-Feb-2022 09:00	117.47	70	C	C	F	C	F	C	80	-117.47
24-Feb-2022 10:00	112.78	80	C	C	D	C	D	C	90	-112.78
24-Feb-2022 11:00	107.58	90	F	F	F	F	D	F	90	0
24-Feb-2022 12:00	105.02	90	F	F	F	F	F	F	90	0
24-Feb-2022 13:00	105.10	90	F	F	F	F	F	F	90	0
24-Feb-2022 14:00	112.40	90	F	F	F	F	F	F	90	0
24-Feb-2022 15:00	113.73	90	F	F	F	F	F	F	90	0
24-Feb-2022 16:00	146.57	90	D	D	D	D	D	D	80	+146.57
24-Feb-2022 17:00	155.38	80	D	D	D	D	D	D	70	+155.38
24-Feb-2022 18:00	134.74	70	C	C	D	C	D	C	80	-134.74
24-Feb-2022 19:00	110.07	80	C	C	F	C	D	C	90	-110.07
24-Feb-2022 20:00	104.53	90	F	F	F	F	D	F	90	0
24-Feb-2022 21:00	109.95	90	F	F	F	F	D	F	90	0
24-Feb-2022 22:00	98.51	90	F	F	F	F	F	F	90	0
24-Feb-2022 23:00	94.78	90	F	F	F	F	F	F	90	0

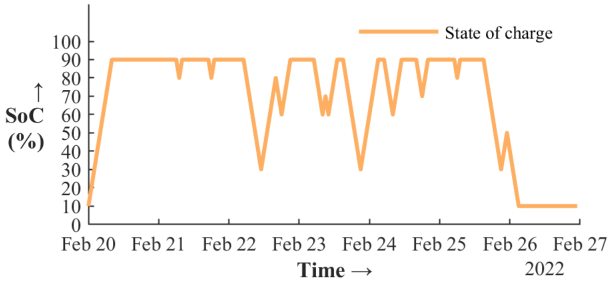

Fig. 5. State of charge of the battery in a week in February 2022.

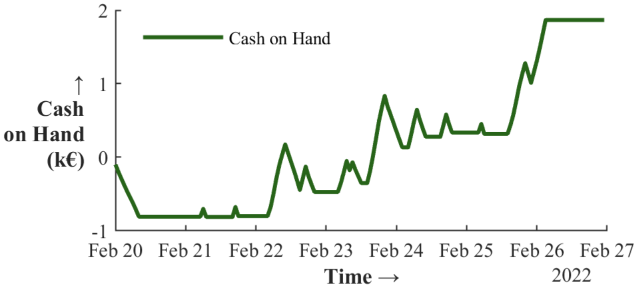

Fig. 6. Cash on hand generation from the battery in a week in Feb 2022.

governing smart contract takes care of controlling the mode of operation of the battery, and the revenue sharing smart contract takes care of sharing revenues with the token holders. In the proposed DAO, the token holders propose the votes to determine the battery's mode of operation considering the utility's real-time price, their electricity price forecast, and the current state of charge of the battery. The mode of operation of the battery energy storage system is decided based on a consensus decision-making procedure after receiving proposed votes from the token holders. The simulation results show that the proposed framework generates considerable revenue for the token holders based on an arbitrary prediction. If the prediction is inaccurate, then there is no guarantee for monetary benefits to the token holders. Finally, the cash on hand will be shared with the shareholder based on the pro-rata share of their initial investment.

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