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Integration of Blockchain-Based Peer-To-Peer Energy Markets in Industrial Water-Energy-Network

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ABSTRACT

Encouraged by the proliferation of distributed renewable energy systems (DRESs), the concept of blockchain based Peer-to-Peer (P2P) energy markets has been gaining momentum in recent years. This promising concept, which allows consumers and prosumers to trade electrical energy directly on a blockchain network without the need for an intermediary, have proven various benefits such as the increase in energy cost savings, improvements in main grid resiliency and more importantly, decarbonization in the long term. Since wastewater treatment systems are known to consume a significant amount of energy to treat influent wastewater such that the effluent meets national discharge standards, the application of this P2P energy trading concept in this industry could prove beneficial to all involved stakeholders. This paper presents an integration of a hierarchical day-ahead P2P energy trading model to the industrial water-energy-nexus (WEN). The first stage introduces a continuous double-sided (CDA) auction market clearing algorithm with the Vickrey-Clarke-Groves (VCG) pricing mechanism deployed on a blockchain framework. The auction mechanism takes the forecasted energy demand/generation as inputs. The next stage proposes a demand-response energy optimization management system for the involved stakeholders. Simulation results show that a P2P-enabled energy market allows consumers to decrease their daily electricity costs by **3.37%** - **5.17%** and allows prosumers to increase their daily electricity profits by **54.08%** - **56.90%**. Furthermore, aggregated load demand during peak hours have been reduced by **11.38%**.

Keywords: Peer-to-Peer (P2P) energy trading, Demand-response optimization, Blockchain, Auction

NONMENCLATURE

Abbreviations

CAES	Compressed Air Energy Storage
CDA	Continuous Double-sided Auction
HRT	Hydraulic Retention Time
SRT	Solid Retention Time
VCG	Vickrey-Clarke-Groves
VSS	Volatile Suspended Solids
WDP	Winner Determination Problem
WWTP	Wastewater Treatment Plant
ZIP	Zero-Intelligence Plus

Symbols

i	*Consumer WWTP index*
θ_t	Target price at time t for sellers and buyers
$\mathcal{R}_t$	Random coefficient
q_{tp_t}	The actual transacted price at time t for sellers and buyers
$\mathcal{A}_t$	Perturbation factor that randomly alters the target price for sellers and buyers
ϕ	Momentum coefficient for sellers and buyers for entire trading duration
β	Learning rate for sellers and buyers for entire trading duration
ω_t	Update parameter at time t for sellers and buyers
E_b/E_a	Cleared volume of electricity of buyer/seller
$E_{maxDemand}$	Maximum demand of consumer
E^{PV}	Generated PV energy
$\bar{p}_t^{grid}/\underline{p}_t^{grid}$	Buy-From-Grid/Sell-to-Grid Utility Price
p_b/p_a	Submitted bid/ask price

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$\dot{a}_{i,t}^{charged}$ $/\dot{a}_{i,t}^{discharged}$	mass flow rate of air directed into/out of the CAES
$\dot{a}_{i,t}^{treatment}$	Mass flow rate of air into treatment
$m_{i,t}^{CAES}$	Mass of air stored in CAES
$\dot{v}_{i,t}^{influent}$	Volumetric flow rate of influent wastewater
$\dot{v}_{i,t}^{charge}$ $/\dot{v}_{i,t}^{discharge}$	Volumetric flowrate of wastewater directed in/out of wastewater storage
$\dot{v}_{i,t}^{treatment}$	Volumetric flow rate of wastewater treated
$v_{i,t}^{tank}$	Volume of water stored in tank
$v_{i}^{tankMax}$	Maximum tank volume
$E_{i,t}^{compression}$	Energy needed for pump compression
$\mathbb{P}_{i,t}^{CAES}$	Pressure of air in CAES
$\mathbb{P}^{atmosphere}$	Atmospheric Pressure
$\mathbb{V}_{i,t}^{CAES}$	Volume of air in CAES
$E_{i,t}^{aeration}$	Energy needed by aerators

1. INTRODUCTION

The energy landscape has visibly evolved over the past decade. Global electrification rate has boosted from 83% in 2010 to approximately 90% in 2018 [1], and the renewable energy share in the overall mix of energy consumption has increased from 16.3% in 2010 to approximately 28% in 2020 [2]. The proliferation of distributed renewable energy systems (DRESs) into the global energy mix demands for a paradigm shift towards a decentralized and flexible energy market. Therefore, this has resulted in the emergence of a new type of energy market which has been gaining significant momentum in recent years: A peer-to-peer (P2P) energy trading market [3].

Unlike the centralized conventional approach where users purchase electricity from the main utility grid, a P2P energy trading market allows users to buy/sell electricity from each other in a decentralized manner, without the need to go through a central intermediary. The successful implementation of a P2P energy trading model depends heavily on several factors [4]. Firstly, a P2P energy market requires a subgroup of the participants to have energy production capabilities (prosumers) and another subgroup of participants who buys the energy for consumption (consumers) [5]. Also, these market participants should be connected on the grid, preferably with smart-grid technologies such as smart meters that monitors the performance of the P2P energy network [6]. Most importantly, there must be an efficient market clearing mechanism in place on a secured platform that allows buyers and sellers to communicate and transact directly with each other [7].

Research has shown that the P2P energy trading market promises various benefits such as an increased uptake in renewable energy deployment, higher main grid resiliency through peak load scheduling, increased social welfare, reduced electrical costs for consumers, and long-term decarbonization as energy markets transit into low-carbon energy systems [8]–[11].

Yet to the best of the author's knowledge, there has been a lack of research into the application of a P2P energy trading model in an industrial setting, particularly within an industrial WEN. There exists an important and intricate relationship between wastewater treatment and energy in an industrial setting. Most energy production requires water and discharges wastewater as a product, while treatment of these wastewater requires a significant amount of energy [12]. Coupled with the forecasted augmentation in the number of global wastewater treatment facilities, where the wastewater treatment market size is estimated to surpass USD 456.68 billion by 2026 [13], energy security within the industrial WEN is of critical importance. With the promised benefits of a P2P energy trading market, this concept could potentially be integrated into the industrial WEN.

2. BACKGROUND

To understand how academic interest in P2P energy trading have peaked over the past few years, a bibliometric analysis is preformed to chart out the temporal developments in the relevant literature, and to identify co-occurring keywords across the relevant literature. The bibliometric analysis first considers 758 literatures obtained from Web of Science that have a primary research focus on P2P energy trading. As seen in **Error! Reference source not found.**, there has been a steady increase in the number of related publications over the past 7 years.

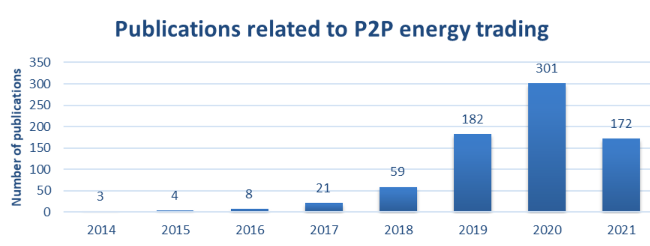

Figure 1. Annual count of related publications to P2P energy trading and blockchain

Building on the results of the forecasted energy, the bedrock of the P2P energy trading market is an efficient auction and pricing mechanism. In most of the related literature that researches into P2P energy trading, a two-sided continuous double auction has been simulated [10], [14]–[17]. Spurred by the three principles of decarbonization, decentralization, and digitalization, the energy market has positioned itself towards a decentralized approach with an increased emergence of microgrids, virtual power plants, and P2P energy markets [18]. Blockchain, a distributed ledger technology, can be used to benefit this shift towards decentralization. Blockchain uses a secured and transparent shared ledger, where transactions can be performed via the smart contracts distributed on the platform. A novel approach undertaken by this paper, is the implementation of the P2P energy trading model in an industrial WEN. One reason behind this implementation arises from the fact that WWTPs are highly energy intensive, hence would potentially benefit from P2P energy trading.

3. METHODS

3.1 P2P Trading Model Formulation

The proposed P2P energy trading model would be presented and simulated step-by-step as seen in Figure 2.

i. A continuous double auction (CDA), that utilizes the forecasted energy demand/generation, implemented on the Vickrey-Clarke-Groves (VCG) pricing mechanisms would be simulated in the cyber layer to clear the P2P energy market.

ii. A demand-response energy management model for both the consumers and energy suppliers would be simulated.

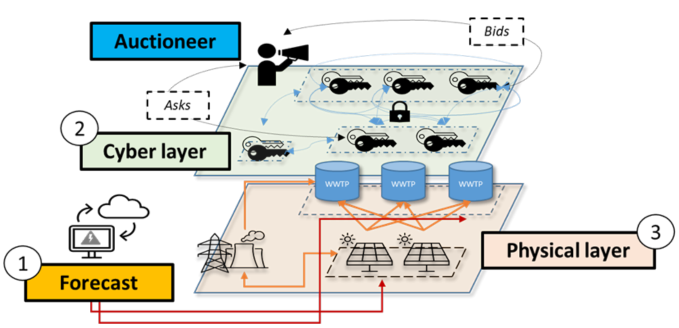

Figure 2. Trading model architecture for industrial WEN

3.2 Market Participant Bidding/Asking Strategy

Before the market clearing algorithm can take effect, buyers and sellers must first submit their bids/asks to the auctioneer. To model the bidding/asking behaviour of the market participants, a Zero-Intelligent-Plus (ZIP) model has been implemented [19]. The submitted bidding/asking price p_{bp} for buyer i and seller j respectively at time t, is formulated as seen in Equation (1) and (2):

$$p_{bp_{i,t}} = \lambda_{lp_i}\left(1 + \mu_{pm_{i,t}}\right), where\ \mu_{pm_{i,t}} \in [-1,0] \quad (1)$$

$$p_{bp_{j,t}} = \lambda_{lp_j}\left(1 + \mu_{pm_{j,t}}\right), where\ \mu_{pm_{j,t}} \in [0,\infty) \quad (2)$$

λ_{lp} represents the maximum limit price that buyer i is willing to buy and the minimum limit price that seller j is willing to sell for. μ_{pm} represents the profit margin factor for the buyers and sellers. The profit margin μ_{pm} for all sellers and buyers is updated using Equations (3) – (5).

$$\mu_{pm_{t+1}} = \frac{p_{bp_t} + \omega_t}{\lambda_{lp}} - 1 \quad (3)$$

$$\omega_{t+1} = \phi\omega_t + (1-\phi)\beta\left[\theta_t - p_{bp_t}\right] \quad (4)$$

$$\theta_t = \mathcal{R}_t\, q_{tp_t} + \mathcal{A}_t \quad (5)$$

The pseudo-code determines whether the buyer increases or decreases the profit margin μ_{pm} is as shown in Figure 3.

Algorithm 1: Pseudo-code for ZIP bidding strategy - Buyers

Result: Obtain Profit Margin μ_t and Update Parameter ω_t at time t
initialization at t = 7;
while $8 \leq t \leq 18$ **do**
  begin auction bidding process;
  if $p_{bp_{t-1}} \geq q_{t-1}$ **then**
    Buyer should increase profit margin;
    $\mathcal{R}_t \leftarrow \mathcal{N}(0.95, 1.00)$;
    $\mathcal{A}_t \leftarrow \mathcal{N}(-0.5, 0.0)$;
  else
    Buyer should decrease profit margin;
    $\mathcal{R}_t \leftarrow \mathcal{N}(1.00, 1.05)$;
    $\mathcal{A}_t \leftarrow \mathcal{N}(0.0, 0.5)$;
  end
end

Figure 3. Pseudo-code for ZIP trading strategy implementation for buyers

3.3 Vickrey-Clarke-Groves (VCG) Pricing Mechanism

Bids/asks submitted to the auction platform would be cleared optimally using the Winner Determination Problem (WDP), which is a combinatorial optimization problem that maximizes social welfare, which is formally defined in Equations (6) – (12).

The utilities from the VCG pricing mechanism for the WWTP consumers at each timestep t, is formulated as shown in Equation (13). As mentioned previously, due to the non-budget balanced nature of the VCG pricing mechanism, a pre-defined fractional transactional cost, *c* ,for all users is implemented to ease additional subsidies required for implementing a VCG pricing mechanism [20].

$$\boldsymbol{Maximize}: \ \mathcal{J}^{*}_{market}\left(E_{b_{(i,d,t)}}, E_{a_{(j,s,t)}}\right) \tag{6}$$

$$= Max. \sum_{i}^{I}\sum_{d}^{D} p_{b_{(i,d,t)}} \times E_{b_{(i,d,t)}}$$

$$- \sum_{j}^{J}\sum_{s}^{S} p_{a_{(j,s,t)}} \times E_{a_{(j,s,t)}}$$

$$\boldsymbol{subject\ to}:$$

$$\sum_{i}^{I}\sum_{d}^{D} E_{b_{(i,d,t)}} = \sum_{j}^{J}\sum_{s}^{S} E_{a_{(j,s,t)}} \ , \forall i, \forall j, \forall t \tag{7}$$

$$0 \leq \sum_{d}^{D} E_{b_{(i,d,t)}} \leq E_{maxDemand_{(i,t)}} \ , \forall i, \forall d, \forall t \tag{8}$$

$$0 \leq \sum_{s}^{S} E_{a_{(j,s,t)}} \leq E^{PV}_{j,t} \ , \forall j, \forall s, \forall t \tag{9}$$

$$p_{b_{(i,d,t)}} \leq \bar{p}^{grid}_{t} \tag{10}$$

$$p_{a_{(j,s,t)}} \geq \underline{p}^{grid}_{t} \tag{11}$$

$$E_{b_{(i,d,t)}}, E_{a_{(j,s,t)}}, p_{b_{(i,d,t)}}, p_{a_{(j,s,t)}} \geq 0 \tag{12}$$

$$\mathcal{U}^{*}_{VCG_{(i,t)}} = (1-c)\sum_{d}^{D_t}\left(p_{b_{(i,d,t)}} - \tilde{p}_{b_{(i,d,t)}}\right) E^{*}_{b_{(i,d,t)}} \ , \quad \forall i \tag{13}$$

$$p_{VCG_{i,t}} = \mathcal{U}^{*}_{VCG_{(i,t)}} - \left[\mathcal{J}^{*}_{market}(\mathcal{A}) - \mathcal{J}^{*}_{market}(\mathcal{A}^{-i})\right] \ , \quad \forall i \tag{14}$$

Equations (14) demonstrates the Clarke's pivot rule for buyer i, where the social welfare that a buyer can contribute to the P2P market for his participation is $[\mathcal{J}^{*}_{market}(\mathcal{A}) - \mathcal{J}^{*}_{market}(\mathcal{A}^{-i})]$.

$\mathcal{J}^{*}_{market}(\mathcal{A}^{-i})$ represents the optimal maximum social welfare when buyer i is not participating in the market. Clarke's pivot rule proposes that the buyer will pay his cleared bidding price minus his contribution towards the overall social welfare of the market, while the seller will receive his cleared asking price plus his contribution towards the overall social welfare of the market.

3.4 Blockchain Experimental Set-Up

For P2P energy market applications, the blockchain should be able to perform transactions quickly and efficiently. It should also be easily scalable to host a large network of prosumers and consumers. Additionally, in a P2P energy market, transactions contain a large volume of sensitive data and information. Hence, a permissioned-consortium network would be the most ideal blockchain platform for P2P energy market implementation. The Hyperledger Fabric blockchain architecture [21] for this thesis's proposed P2P energy trading model is as shown in Figure 4.

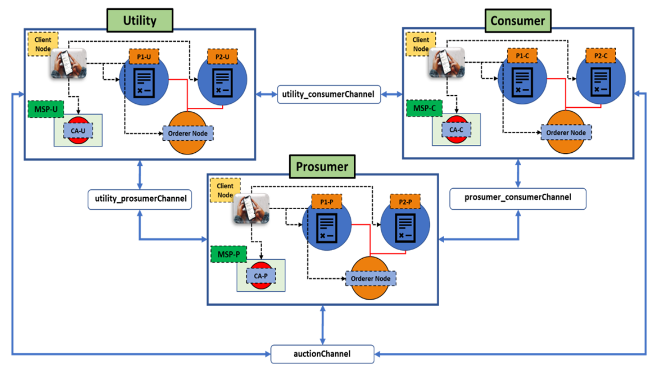

Figure 4.Proposed P2P energy trading network blockchain architecture

3.5 Demand Response Optimization Model

Illustrated in Figure 5, consumer WWTPs are proposed to have a compressed air energy storage (CAES) capability as well as a temporary wastewater storage unit. The key idea of demand response optimization for the consumers is to store air and wastewater when electricity prices are high and release them for treatment when electricity prices are low.

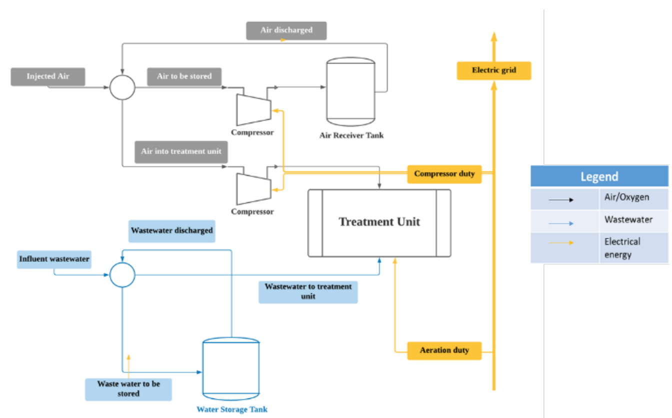

Figure 5. WWTP demand response architecture and capabilities

The objective of the consumer WWTPs, as seen in Equation (19), is to minimize the electrical costs and maximize the revenue from wastewater treatment. $p_t^{wwTreated}$ represents the price charged by WWTPs for treating wastewater, while $\dot{v}_{i,t}^{wwTreated}$ represents the volume of wastewater treated by consumer WWTP i at time t.

$$\boldsymbol{Min.} \sum_t^T \sum_i^I p_t^{buyFromGrid} E_{i,t}^{buyFromGrid} + p_{i,t}^{P2P} E_{i,t}^{P2P} - p_t^{wwTreated} \dot{v}_{i,t}^{wwTreated} \tag{15}$$

The constraints (Equations 16 – 33) for the consumer WWTPs model can be categorized into three segments: 1) Air constraints, 2) Wastewater constraints, and 3) Energy constraints. Equations 31 and 32 are adapted from [22].

Air Constraints

$$\dot{a}_{i,t}^{injected} + \dot{a}_{i,t}^{discharged} - \dot{a}_{i,t}^{charged} - \dot{a}_{i,t}^{treatment} = 0, \forall i, \forall t \tag{16}$$

$$m_{i,t+1}^{CAES} = m_{i,t}^{CAES} + \dot{a}_{i,t}^{charged} - \dot{a}_{i,t}^{discharged}, \forall i, \forall t \tag{17}$$

$$\dot{a}_{i,t}^{discharged} \le \beta_{1_{i,t}} m_{i,t-1}^{CAES}, \forall i, \forall t \tag{18}$$

$$\dot{a}_{i,t}^{charged} \le \beta_{2_{i,t}} \left(m_i^{CAESmax} - m_{i,t-1}^{CAES}\right), \forall i, \forall t \tag{19}$$

$$\beta_{1_{i,t}} + \beta_{2_{i,t}} \le 1, \forall i, \forall t \tag{20}$$

$$m_{i,t}^{CAES} \le m_i^{CAESmax}, \forall i, \forall t \tag{21}$$

$$\mathbb{P}_{i,t}^{CAES} = \frac{\left(\frac{m_{i,t}^{CAES}}{28.97} \times 8.314 \times 298.15\right)}{m_{i,t}^{CAESmax}}, \forall i, \forall t \tag{22}$$

$$\dot{a}_{i,t}^{treatment} \ge \left[\left(COD_{i,t}^{in} - COD_{i,t}^{out}\right) - \frac{1.42 \times HRT_i \times VSS_i}{SRT_i}\right] \times \dot{v}_{i,t}^{treatment} \times \frac{28.97}{31.98\ (0.2)} \tag{23}$$

Water Constraints

$$\dot{v}_{i,t}^{influent} - \dot{v}_{i,t}^{charge} + \dot{v}_{i,t}^{discharge} - \dot{v}_{i,t}^{treatment} = 0, \forall i, \forall t \tag{24}$$

$$v_{i,t+1}^{tank} = v_{i,t}^{tank} + \dot{v}_{i,t}^{charge} - \dot{v}_{i,t}^{discharge}, \forall i, \forall t \tag{25}$$

$$\dot{v}_{i,t}^{discharge} \le \beta_{3_{i,t}} v_{i,t-1}^{tank}, \forall i, \forall t \tag{26}$$

$$\dot{v}_{i,t}^{charge} \le \beta_{4_{i,t}} \left(v_i^{tankMax} - v_{i,t-1}^{tank}\right), \forall i, \forall t \tag{27}$$

$$\beta_{3_{i,t}} + \beta_{4_{i,t}} \le 1, \forall i, \forall t \tag{28}$$

$$\sum_t^T \dot{v}_{i,t}^{influent} = \sum_t^T \dot{v}_{i,t}^{treated}, \forall i \tag{29}$$

Energy Constraints

$$E_{i,t}^{P2P} + E_{i,t}^{buyFromGrid} - E_{i,t}^{compression} - E_{i,t}^{aeration} = 0 \tag{30}$$

$$E_{i,t}^{compression} = \left[\mathbb{P}_{i,t}^{CAES} \times \mathbb{V}_{i,t}^{CAES} \times \ln\left(\frac{\mathbb{P}^{atmosphere}}{\mathbb{P}_{i,t}^{CAES}}\right)\right] + \left(\mathbb{P}_{i,t}^{CAES} - \mathbb{P}^{atmosphere}\right) \times \mathbb{V}_{i,t}^{CAES} \tag{31}$$

$$E_{i,t}^{aeration} = \dot{a}_{i,t}^{treatment} \times 0.2 \times 1e^{-3} \times \frac{1}{1.5} \times \frac{1}{C_i} \tag{32}$$

$$\sum_i^I E_{i,t}^{P2P} \le \sum_j^J E_{i,t}^{PV} \tag{33}$$

4. CASE STUDY AND RESULTS DISCUSSION

A case-study is implemented, where the proposed hierarchical P2P energy trading model is tested for an industrial WEN with 27 market participants (2 solar farms acting in the capacity of prosumers, and 25 wastewater treatment plants acting in the capacity of consumers). The assumptions and chosen parameters were presented and explained in Chapter 3. All the simulations in the case studies are performed on a computer running on an Intel Core i7 9th generation processor at 2.60 GHz and 16 GB RAM, using Python v3.8.7. All optimization was performed using Gurobi Optimizer 9.1.

Based on the submitted bids and asks, the CDA market would be cleared by the Winner Determination Problem which aims to maximize the total social welfare. The demand and supply curves for each simulated time step during trading hours are seen in **Error! Reference source not found.**. The intersection between the demand and supply curves would be the uniform market clearing price. For each consumer WWTP, the daily total amount of energy cleared in the P2P energy trading market is expressed as a percentage of the daily total amount of energy submitted as bids. The P2P market determined price signals would serve as inputs into the demand-response energy management system for the consumer WWTPs. The objective of the consumer WWTPs is to minimize the electrical costs and maximize the revenue from wastewater treatment.

For example, looking specifically at consumer indexed 3, as seen in **Error! Reference source not found.**, during non-trading hours when prices of electricity are higher, the load consumption was shifted from peak hours to off-peak hours. The total aggregated load consumption for all consumer WWTPs during peak hours has been shaved off by 11.38%. The daily cost for industrial WWTP consumers who participate in P2P trading would decrease by a range of 3.37% - 5.17%. The daily profit for prosumers who participate in P2P trading would increase by a range of 54.08% - 56.90%, as compared to a P2P disabled energy market.

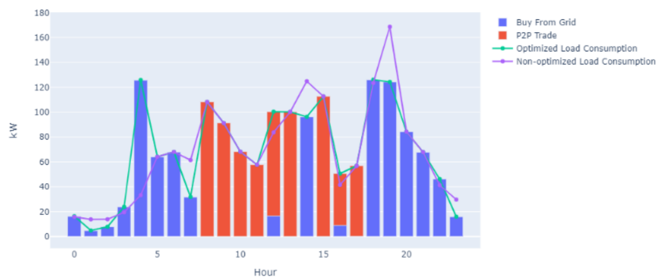

Figure 6. Optimized WWTP day-ahead load schedule for consumer indexed 3 - P2P Trading Enabled

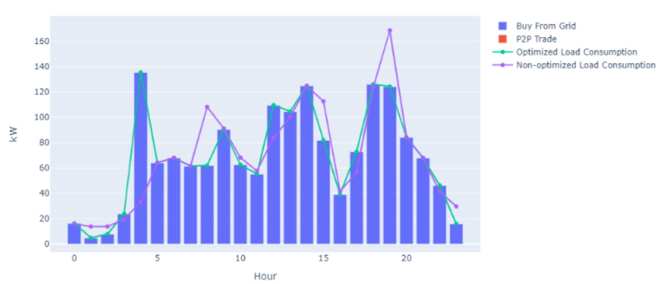

Figure 7. Optimized WWTP day-ahead load schedule for consumer indexed 3 - P2P Trading Disabled

5. CONCLUSIONS

This paper proposed the development of a hierarchical P2P energy trading model that can be applied towards an industrial WEN. Users would submit bids/asks to the auctioning platform using a continuous double-sided auction modelled via the ZIP algorithm, and the market would be cleared optimally using WDP incorporated with the VCG pricing mechanism. The cleared price and quantity for each consumer and prosumer would be sent to the demand-response optimization model. In the industrial WEN, consumer WWTPs were proposed to have a CAES capability as well as a temporary wastewater storage unit, that allows consumers to store air and wastewater when electricity prices are high and release them for treatment when electricity prices are low. In the industrial WEN, a P2P-enabled energy market allows consumers to decrease their daily electricity costs by 3.37% - 5.17% and allows prosumers to increase their daily electricity profits by 54.08% - 56.90%. Therefore, in terms of economic benefits, it is more beneficial for consumers WWTPs partake in the P2P energy trading market as the consumers enjoy higher daily cost savings.

In this paper, one limitation in the industrial WEN case study results from the lack of accessibility to historical WWTP load demand hourly data. Also in future work, the scalability of a high volume of users in the blockchain network should be studied separately. Also, the incorporation of a penalty element that penalizes the users based on deviations in real-time energy profile from the day-ahead short-term energy forecast should be considered

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