

A Coalition Framework for Increasing Market Participation of Electrolysers and Renewable Energy Sources

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Abstract—The generation of electricity from renewable energy sources is highly volatile and intermittent. The excess energy generated by renewable energy sources can be used to generate green hydrogen using electrolysers, thus generating energy demand for the excess energy and maximizing the utilization of renewable energy sources. The paper presents a decentralized framework through which electrolysers and renewable energy sources form a coalition to balance the energy production and demand, maximize the overall revenue and encourage early adopters of electrolyser technology without the need of public subsidies. This guarantees a reasonable distribution of revenue for all participants in the coalition regardless of their entry time into the market. This approach will naturally evolve into a market model in which the most efficient electrolysers will succeed as soon as the investment cost settles and the supply chains develop. Thus, potential electrolyser technology adopters are motivated to participate in a peer-to-peer electricity trading market for the production of hydrogen and drive forward the hydrogen economy.

Index Terms—Green Hydrogen, electrolysis, cooperative control, smart grid

I. INTRODUCTION

The EU has set itself a legally binding target of achieving net-zero greenhouse gas emissions by 2050. This is codified in the European Climate Law, which also sets an intermediate target of at least a 55% reduction by 2030, compared to 1990 levels [1]. Hydrogen is enjoying a renewed and rapidly growing attention in Europe and around the world. Hydrogen can be used as a feedstock, a fuel or an energy carrier and storage, and has many possible applications across industry, transport, power and the buildings sectors. Most importantly, it does not emit carbon dioxide and almost no air pollution when used as fuel for fuel cells. It thus offers a solution to decarbonise industrial processes and economic sectors, where reducing carbon emissions is both urgent and hard to achieve.

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To facilitate this, Europe has put forward an ambitious plan to ramp up the green hydrogen generation [2].

The distributed renewable energy sources, mainly wind and solar, along with the intermittent nature of the generation creates periods of electrical energy overproduction termed as surplus and periods of under generation termed as deficit. Currently, due to lack of sufficient storage capacity, such surplus energy is wasted by shutting down renewable power sources, leading to a significant disposal of energy. Several studies have concluded that battery storage will not be sufficient to avoid this waste and in many cases even unfavorable [3]. As renewable energy generation is predicted to grow several times in the future, the amount of intermittent electrical energy surplus will also be increasing.

Renewable hydrogen generation and storage during an energy surplus is a solution to balance electrical energy production and demand and increase the utilization of renewable energy sources. During the surplus period, the cost of electricity also decreases, which could be used to generate renewable hydrogen at a low price. A peer-to-peer (P2P) trading platform offers a marketplace for energy providers to trade renewable energy generated at a better price, encouraging the deployment of distributed generation. Similarly, P2P trading allows consumers to have control over their electricity consumption and its price, increasing flexibility in the system. The P2P electricity trading empowers electricity providers and consumers, leading to increased deployment and flexibility of renewable energy in the grid [4].

The P2P platform facilitates the electrolyser participants to seamlessly bargain over electricity price and reach an agreement with renewable energy providers. As long as the surplus energy generation is greater than the installed electrolyser capacity of all the participants, the market favors the electrolyser participants by making available electricity at lower prices. But the surplus is not always constant. There are time intervals, when the surplus is lower than the electrolyser demand leading to competition between consumers for limited energy availability.

The continuous advancement in electrolyzer technology is

leading to a significant reduction in costs. The projections indicate that the capital costs of the electrolyzer will decrease from the current 900 €/kW to 450 €/kW by 2030 and is expected to further reduce to 180 €/kW by 2040 [2]. Simultaneously, conversion rates, which is the amount of hydrogen produced for unit energy, are expected to improve. At present the conversion rates are in the range of 18 g/kWh to 25 g/kWh and is expected to be in the range of 21 g/kWh to 28 g/kWh by 2030 [5] [6]. The electrolyser participants who enter later in the business have an advantage over the early adopters of the technology [7], due to a higher conversion rate and lower investment. This leads to a high possibility that early electrolyser participants may face an exit situation, either because of not obtaining matched entities or not having access to the expected price from the market. This uncertainty in price and efficiency encourages the potential electrolyser participants to wait and watch until the technology and investment costs settle.

One way to overcome this is by introducing subsidies, so that the impact of cost reduction with time is reduced. Parallels can be drawn to the rise of renewable energy sources, which is fueled by various support policies and frameworks. A similar support policy will be ineffective in the case of electrolyser participants, because unlike renewable energy sources, the variable costs associated with green hydrogen generation are significantly higher and have a greater impact on the profit of electrolyser participants. That is, significant capital in the form of consumer levy will be required to sustain the green hydrogen business by compensating for not only the fixed cost but also the variable costs associated with generation and the lost revenue due to lack of demand for green hydrogen.

The advantages of cooperative behaviour in a P2P market mechanism incorporating multi-energy coupling is presented in [8], where the advantage of forming an electricity-only trading coalition and an electricity-heat trading coalition is presented. [9] proposes a cooperative game that ensures the survival of small-scale prosumers at a risk of market-exit, when they do not produce enough surplus electricity to cater the power needs of a single consumer. The [8] [9] lacks a decentralized framework that optimally utilizes renewable energy for hydrogen production, failing to account for electrolyser fleet diversity, dynamic hydrogen pricing, and real-time efficiency variations. This work introduces a decentralized coalition framework to optimize energy utilization, balance the grid, and ensure a fair share of revenue for all participants.

The paper is structured as follows. Section II explains the system model followed by Section III describing the decentralized coalition framework. Section IV illustrates the results generated using the proposed method, and the paper concludes with Section V

II. SYSTEM MODEL

A simulation model is designed to replicate a real market scenario involving renewable energy sources as providers and electrolyser operators as consumers. Renewable energy providers are assumed to operate with wind and solar plants. The variable θ_p denotes the set of all providers. The energy

consumers are represented by θ_c , s.t. $\theta_p \cup \theta_c = \theta_M$. The set θ_M is the set of all market participants considered in the model. The simulation time period is T and providers and consumers agree on sharing power and revenue, in advance, at every instant $t_0 = n\Delta t_p$, $n = 1, 2, \dots, T/\Delta t_p$. At every instant of time $t \in [n\Delta t_p, (n+1)\Delta t_p]$ it is assumed that no participant can be a provider and consumer of electricity at the same time, s.t. $\theta_s \cap \theta_b = \emptyset$, where \emptyset is an empty set.

A. Renewable Energy Providers

The renewable energy providers can predict their energy generation in advance using the weather data and sell the future energy generation capacity using an energy exchange platform. The profit function $B_p(n)$ of the renewable energy market participants at every discrete time is represented by,

$$B_p(n) = \sum_{j \in \theta_p} \left(E_{T,j}(n) \cdot \varphi_{el,j}(n) - k_{f,j}(n) \right) \quad (1)$$

where the instantaneous generated energy during the period t_p is calculated from the average power $P_{T,j}(n)$ as $E_{T,j}(n) = P_{T,j}(n) \cdot \Delta t_p$.

The costs associated with renewable energy providers consist of investment and maintenance costs, which are incorporated into the variable $k_{f,j}$. The revenue for providers comes from the sale of electrical energy $E_{T,j}$ at a price per unit energy of $\varphi_{el,j}$. The variable $k_{f,j}$ is computed for each discrete time step n for all participants as,

$$k_{f,j}(n) = \frac{P_{cap,j} \cdot \Omega_j \cdot \Delta t_p}{\sigma_{T,j}} \quad \forall j \in \theta_p \quad (2)$$

where, Ω_j is the installation investment cost, $P_{cap,j}$ is the installation capacity and $\sigma_{T,j}$ is the lifespan of the system.

B. Electrolyser Participants

The electrolyser participants obtain the required electrical energy from renewable energy providers. A P2P energy exchange platform facilitates consumers and providers to seamlessly bargain over price and reach a power sharing agreement. In the model, electrolysers with varying conversion rates are considered. The profit function of the j^{th} electrolyser operators $B_{c,j}(n)$ is the difference between the revenue from selling hydrogen at a price per unit quantity of $\varphi_{H2,j}(n)$ and the expenses incurred in buying electricity. Thus the total profit $B_c(n)$ of electrolyser operators can be expressed as:

$$B_c(n) = \sum_{j \in \theta_c} \left(E_{T,j}(n) \cdot \lambda_{e,j} \cdot \varphi_{H2,j}(n) - k_{f,j}(n) - E_{T,j}(n) \cdot \varphi_{el,j}(n) \right) \quad (3)$$

The main expense for the consumer are the costs associated with the purchase of electrical energy $E_{T,j}(n)$ at a cost per unit quantity of $\varphi_{el,j}(n)$. The variable costs associated with handling of hydrogen, are neglected for simplicity. The conversion rate of an electrolyser, which is the quantity of hydrogen produced per unit energy is represented by the variable $\lambda_{e,j}$.

C. Market Model

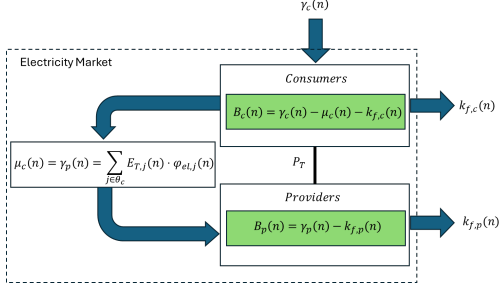


Fig. 1. Market Model

A market is modeled as illustrated in Fig. 1. A market with renewable energy providers and electrolyser consumers is considered. The electrical energy from the providers is traded in the P2P market. The consumers use this energy to generate green hydrogen. The revenue $\gamma_{c,j}(n)$ generated by selling hydrogen in the hydrogen market at a unit price of $\varphi_{H2,j}(n) \forall j \in \theta_c$ is given in (4).

$$\forall j \in \theta_c, \gamma_{c,j}(n) = E_{T,j}(n) \cdot \lambda_{e,j} \cdot \varphi_{H2,j}(n) \quad (4)$$

$$\gamma_c(n) = \sum_{j \in \theta_c} \gamma_{c,j}(n) \quad (5)$$

The total revenue generated by the electrolyser operators is given by $\gamma_c(n)$ in (5), where $E_{T,j}(n)$ is the energy transacted between producers and consumers. Fig. 1 illustrates that the revenue generated by consumers are distributed to the providers based on the electricity cost $\varphi_{el,j}$ as illustrated in (6)

$$\mu_c(n) = \gamma_p(n) = \sum_{j \in \theta_c} (E_{T,j}(n) \cdot \varphi_{el,j}(n)). \quad (6)$$

The fixed cost of the participants account for the investment cost and the maintenance cost. The variables $k_{f,c}(n) = \sum_{j \in \theta_c} k_{f,j}(n)$ and $k_{f,p}(n) = \sum_{j \in \theta_p} k_{f,j}(n)$ are the fixed cost of the consumers and provider respectively.

Fig. 1 illustrates, that the revenue flows into the electricity market from the sale of hydrogen generated by consumers and the expenses that flows out of the market are the fixed costs associated with investment and maintenance. Thus the sum of profits of each participant is given by $B_p(n) + B_c(n) = \gamma_c(n) - k_{f,c}(n) - k_{f,p}(n)$

III. DECENTRALIZED COALITION FRAMEWORK

The coalition framework includes a predefined set of rules and local interactions at individual level, leading to a collective intelligence, thereby balancing the grid and, at the same time, maximizing revenue from hydrogen generation. The rules of the framework are illustrated in Fig. 2, which includes two parts

- 1) Power distribution agreements
- 2) Revenue distribution agreements

The power distribution agreement balances the grid and maximizes the revenue from the sale of hydrogen for the community of participants. Participants are connected through a secure MQTT-based platform. A certification authority issues each participants with a unique ID $p_j, \forall j \in \theta_M$ and a certificate. The certificate and digital signature ensure trust and authenticity among participants. A detailed discussion of the MQTT-based platform, certification process and the platform is beyond the scope of this paper.

The paper proposes a decentralized chain-forming algorithm based on leader selection and emergent sort to maximize the revenue from sale of hydrogen as illustrated in Algorithm 1. This includes a chain forming period Δt_c and a relay period Δt_r , s.t. $\Delta t_c + \Delta t_r < \Delta t_p$. All participants subscribe to topics *claim*, *concede*/ p_j and *challenge*/ p_j on the MQTT platform. A chain is formed by using links, which is defined as $ln_j = [p_-, v_-], \forall j \in \theta_M$, where p_- is the ID and v_- is the sorting value of the preceding participant. Participants in the provider group and consumer group compete to be leader in the chain by publishing a message C_m on the topic *claim* during the period Δt_c , which results in the formation of a chain in each group. The claim message is defined as $C_m = \{p_m, v_m, P_{c/p,m}\}$, where p_m is the ID of the current claim holder, v_m is the sorting value for the participants and $P_{c/p,m}$ is the group demand or generation of participants in the chain formed by the claim holder m , $\forall m \in \theta_M$. For electrolyser participants, the sorting value is based on $\eta_j(n) \forall j \in \theta_c$, such that the most economically efficient electrolyser becomes the leader of the chain. The economical efficiency of an electrolyser is depicted by

$$\eta_j(n) = \lambda_{e,j} \cdot \varphi_{H2,j}(n), \quad (7)$$

which is the revenue generated for a unit energy. For the providers, the sorting value is chosen as the generated power $P_{gen,j}(n) \forall j \in \theta_p$, so as to make the largest energy provider the leader of the chain.

Participants respond to a claim message either with a concede message $C_o = \{p_o, v_o, P_{c/p,o}\}$ or with a challenge message $C_l = \{p_l, v_l\}, \forall o, l \in \theta_M$. Based on the interaction, a chain is built for the consumer group and provider group with one leader in each group. The chain leader maintains the claim C_m with information on the demand and generation of the group. Once the chain formation period Δt_c is complete the provider group leader generates a relay message defined as $R_e = \{p_e, P_e, \gamma_e\}$, where p_e is the ID of the provider group leader, P_e is the total generation of participants in provider group and γ_e is the cumulated revenue from the sale of hydrogen. γ_e is calculated during the relay period Δt_r . The R_e is published to the topic *relay*/ p_m , where p_m is the ID of the consumer group leader.

The message R_e is passed through the chain until the available power P_e is exhausted or until the last link is reached. This ensures that the most economically efficient electrolysers get the maximum share of available power, thus maximizing the revenue from sale of hydrogen based on the optimization problem given by (8a) (8b). During Δt_r the

power transaction agreement is reached between providers and consumers. Power-sharing agreements ensure grid balance and revenue maximization, thus satisfying the first part of the coalition rules depicted in Fig. 2.

$$\text{maximize}_{P_{T,j}} \sum_{j \in \theta_c} E_{T,j}(n) \cdot \lambda_{e,j} \cdot \varphi_{H2,j}(n) \quad (8a)$$

subject to

$$P_{T,c} \leq P_{\text{gen}}, P_{T,c}(n) = \sum_{j \in \theta_c} P_{T,j}(n) \quad (8b)$$

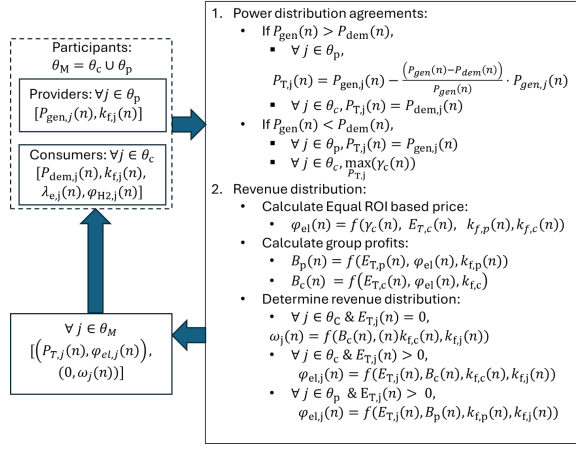


Fig. 2. Coalition Rules

The revenue from the sale of hydrogen at each time period Δt_p is calculated, when the relay message is reverted back to the provider group leader. The provider group leader then publishes a message Pct to topic $pricecnt/$. The message $Pct = \{\gamma_e, E_{T,c}\}$, which contains the value of the total revenue of the consumer group and the total transacted energy $E_{T,c} = E_{T,p} = (P_{\text{gen}} - P_e) \cdot \Delta t_p$, which is then used by all participants to calculate the weighted average price for electricity φ_{el} , so that the provider group and the consumer group get returns proportional to their investment (9).

$$\varphi_{el}(n) = \frac{\gamma_c(n)}{\sum_{j \in \theta_c} E_{T,j}(n)} \cdot \frac{k_{f,p}(n)}{k_{f,c}(n) + k_{f,p}(n)} \quad (9)$$

The weighted average electricity price φ_{el} is used to find the group profit for consumer and provider groups. The fixed cost of the provider group $k_{f,p}$ and the fixed cost of consumer group $k_{f,c}$, are assumed to be constant for every instant of time, since all participants are part of the coalition at every instant of time. The group profit of consumers is given as,

$$B_c(n) = \gamma_c(n) - E_{T,c}(n) \cdot \varphi_{el}(n) - k_{f,c}(n). \quad (10)$$

Similarly the group profit of the provider can be calculated as,

$$B_p(n) = E_{T,p}(n) \cdot \varphi_{el}(n) - k_{f,p}(n). \quad (11)$$

The group profits of the providers and consumers are used to calculate the individual electricity prices for the transacted

energy for each participants and the compensation amount for the consumers ω_j who's energy demands are not met (12)-(15).

$$\varphi_{el,j}(n) = \frac{\gamma_{c,j}(n) - B_c(n) \cdot \left(\frac{k_{f,j}(n)}{k_{f,c}(n)}\right) - k_{f,j}(n)}{E_{T,j}(n)}, \quad (12)$$

$$\forall j \in \theta_c, E_{T,j}(n) \neq 0$$

$$\omega_j(n) = B_c(n) \cdot \frac{k_{f,j}(n)}{k_{f,c}(n)}, \forall j \in \theta_c \quad (13)$$

$$\varphi_{el,j}(n) = \frac{B_p(n) \cdot \frac{k_{f,j}(n)}{k_{f,p}(n)} + k_{f,j}(n)}{E_{T,j}(n)}, \forall j \in \theta_p \quad (14)$$

$$\omega_j(n) = B_p(n) \cdot \frac{k_{f,j}(n)}{k_{f,p}(n)}, \forall j \in \theta_p \quad (15)$$

IV. RESULTS

An electricity market involving eight participants is simulated for a 24 hour duration. This includes four renewable energy sources as providers and four electrolyser operators as consumers. The parameters of the participants are shown in Table I. The set $\theta_p = \{1, 2, 3, 4\}$ are providers and $\theta_c = \{5, 6, 7, 8\}$ is the set of consumers. The lifespan of all renewable energy and electrolyser systems is assumed to be 20 years, and the installation investment cost is taken as 1000 €/kW. Providers can forecast their energy generation and consumers can predict their future demand. Both side come to an agreement on sharing power and revenue for every 15min duration, i.e. $\Delta t_p = 15min$. The sum of profit of all participants from the decentralized coalition framework is compared to the results from an offline optimization as described in the following section.

A. Optimization problem formulation

The optimization problem for the MATLAB optimizer is formulated in (16). The objective is to maximize the sum of profit of the participants i.e., to maximize the revenue $\gamma_j(n)$ and to minimize the expense $\mu_j(n)$, under the assertion of a balanced grid. This is formulated as a minimization function for the MATLAB `fmincon` solver as given in (16). The value of constant $k_{\text{max},j}$ is the maximum revenue possible $\forall j \in \theta_p$, $k_{\text{max},j} = P_{\text{cap},j} \cdot \Delta t_p \cdot \varphi_{el,\text{max}}$ and $\forall j \in \theta_c$, $k_{\text{max},j} = P_{\text{cap},j} \cdot \Delta t_p \cdot \lambda_{e,j} \cdot \varphi_{H2,\text{max}}$.

$$\begin{aligned} \min_{P_{T,j}, \varphi_{el,j}} & \sum_{n=1}^{T/\Delta t_p} \sum_{j \in \theta_M} \left(q_j \cdot (k_{\text{max},j} - \gamma_j(n) + \mu_j(n))^2 \right. \\ & \left. + q_0 \cdot \Delta P_{\text{grid}}(n) \right) \\ \text{s.t.} & \sum_{j \in \theta_p} P_{T,j} \leq P_{\text{gen}}, \sum_{j \in \theta_c} P_{T,j} \leq P_{\text{dem}} \\ & \varphi_{el,\text{min}} \leq \varphi_{el,j} \leq \varphi_{el,\text{max}} \quad \forall j \in \theta_M \end{aligned} \quad (16)$$

The variable $\Delta P_{\text{grid}}(n) = P_{T,p}(n) - P_{T,c}(n)$, is the difference between the sum of transacted power of providers and consumers respectively. The electricity prices are allowed

to be between a range of $(\varphi_{el,min}, \varphi_{el,max})$. The variables q_0 and q_j are the weighting factor. For this test scenario $(-0.50 \text{ €/kWh}, 0.50 \text{ €/kWh})$ is selected as a reasonable price fluctuation region. The variable $\varphi_{H2,max}$, which is the maximum price per unit quantity is assumed to be 4.50 €/kg . The power generation profile, demand profile and hydrogen price profile used for the offline optimization is the same as in Fig. 3(a).

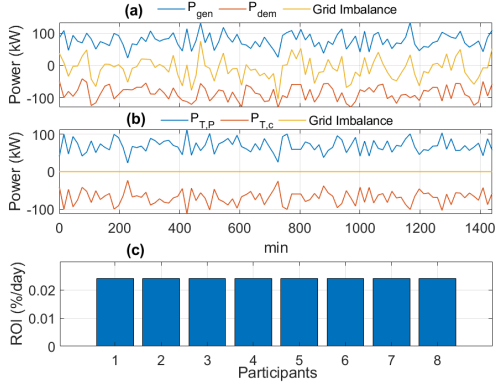


Fig. 3. (a): Grid imbalance from forecasted generation and demand, (b): Grid imbalance from transaction power agreements, (c): Return on investment for participants

B. Decentralized coalition framework

The generation is dependent on the parameters mainly wind speed and solar intensity which fluctuates throughout the day. To introduce volatility in the generation and demand, each participant is induced to generate and demand potentials fluctuating between 0 to $P_{cap,j} \forall j \in \theta_p$. The potential grid imbalance introduced by these volatility is illustrated in Fig. 3(a). The bid price of hydrogen for each consumers also fluctuates to introduce the actual market scenario.

Fig. 3(b) and Fig. 3(c) illustrates the results from the decentralized coalition framework. The power transacted between consumers and providers balanced the grid and also ensured equal return on investment for all participants. The Fig 4(a) illustrates the weighted average price of electricity in the market, which ensured an equal share of revenue between consumers and providers. Fig. 4(b) illustrates the average price fluctuations in the cost of hydrogen. The power transaction between participants is illustrated in Fig 5(a) and Fig 5(b). The proposed algorithm ensured a maximum power share for the most economically efficient electrolyzers, thus maximizing the revenue generation from hydrogen generation. The electrolyzers deprived of power due to power deficit are compensated with revenue returns.

The Fig 5(c) illustrates the comparison of the total profit of participants from the decentralized approach and from the offline optimization as discussed in section IV-A. The results illustrate that the sum of profit of all participants from the decentralized approach is the same compared to the results from the offline optimization approach.

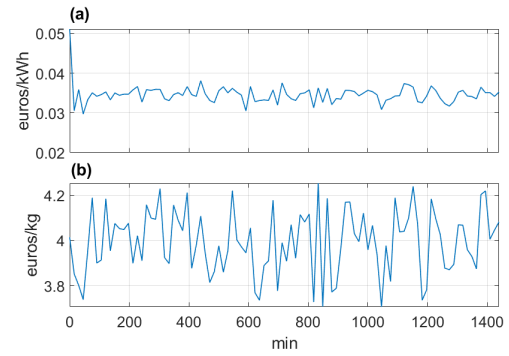


Fig. 4. (a): Weighted average price of electricity, (b): Average hydrogen price

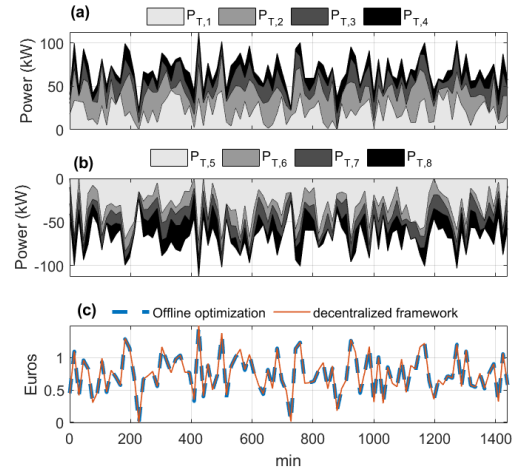


Fig. 5. (a): Providers transacted power, (b): Consumers transacted power, (c): Total Profit

V. CONCLUSION

The paper presents a coalition framework that ensures power distribution to balance the grid and at the same time maximized the revenue from hydrogen generation. The proposed model motivates the investment in electrolyzers as the early investors are not left out of the market once new electrolyzers with technological advancement enter the energy market. The rule based approach ensured maximum revenue generation from hydrogen generation and maximized utilization of the energy surplus from the renewable energy sources. By ensuring the same ROI for all participants the cooperative approach mitigates the risk for early adopters, and this could potentially motivate early investment in green hydrogen generation business until the technology develops and the supply chain matures.

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APPENDIX

TABLE I
PARTICIPANT PARAMETERS

j	$P_{cap,j}$ (kW)	$k_{f,j}$ (€/Δt _p)	$\lambda_{e,j}$ (kg/kWh)
1	50	0.0713	-
2	50	0.0713	-
3	30	0.0428	-
4	20	0.0285	-
5	80	0.1142	0.0161
6	20	0.0285	0.0172
7	20	0.0285	0.020
8	30	0.0428	0.0161

Algorithm 1 Chain algorithm consumer group

```

1: for n = 1 to  $T/\Delta t_p$  and  $j \in \theta_c$  do
2:   subscribe topics: claim/, concede/pj/ and challenge/pj/
3:   get  $C_m$  from topic claim/
4:   if  $C_m$  then
5:     if  $\eta_j(n) < v_m$  then
6:        $[p_o, v_o, P_{c,o}] = [p_j, \eta_j(n), P_{dem,j}(n)]$ 
7:       publish  $C_o$  to topic: concede/pm
8:     end if
9:     if  $\eta_j(n) > v_m$  then
10:       $[p_l, v_l] = [p_j, \eta_j(n)]$ 
11:      publish  $C_l$  to topic: challenge/pm
12:    end if
13:   else
14:      $[p_m, v_m, P_{c,m}] = [p_j, \eta_j(n), P_{dem,j}(n)]$ 
15:     publish  $C_m$  to topic: claim/
16:   end if
17:   while ( $t \in [t_0, t_0 + \Delta t_c]$ ) do
18:     get  $C_o$  from topic: concede/pj/
19:     if  $C_o$  and  $v_- < v_o$  then
20:       cumulate power  $P_{c,m} = P_{c,m} + P_{c,o}$ 
21:        $[p_l, v_l] = [p_o, v_o]$ 
22:       publish  $C_l$  to topic: challenge/p-
23:       update the link  $[p_-, v_-] = [p_o, v_o]$ 
24:     else if  $C_o$  and  $v_- > v_o$  then
25:       cumulate power  $P_{c,m} = P_{c,m} + P_{c,o}$ 
26:       publish  $C_o$  to topic concede/p-
27:     else if  $C_l$  then
28:        $[p_o, v_o, P_{c,o}] = [p_j, \eta_j(n), P_{c,m}]$ 
29:       publish  $C_o$  to topic: concede/pl
30:       if ( $p_j = p_m$ ) then Delete  $C_m$ 
31:     end if
32:   end while
33:   subscribe to topic: relay/pj/
34:   while ( $t \in [t_0 + \Delta t_c, t_0 + \Delta t_c + \Delta t_r]$ ) do
35:     get  $R_e$  from topic: relay/pj
36:     if  $R_e$  and  $P_e > P_{dem,j}$  then
37:       power transaction  $P_{T,j}(n) = P_{dem,j}(n)$ 
38:        $[P_e, \gamma_e] = [(P_e - P_{dem,j}(n)), \gamma_e + \gamma_j(n)]$ 
39:       if ( $p_- = 0$ ) publish  $R_e$  to topic: relay/pe
40:       if ( $p_- \neq 0$ ) publish to topic: relay/p-
41:     else if  $R_e$  and  $P_e \leq P_{dem,j}(n)$  then
42:       generate transaction  $P_{T,j} = P_e$ 
43:        $[P_e, \gamma_e] = [0, \gamma_e + \gamma_j(n)]$ 
44:       publish  $R_e$  to topic: relay/pe
45:     end if
46:   end while
47:   subscribe to topic: pricecnt/
48:    $[\gamma_c(n), E_{T,c}(n)] = [\gamma_e, (P_{gen} - P_e) \cdot \Delta t_p]$ 
49:   estimate price (9) – (15)
50:   Clear  $C_m, C_o, C_l, R_e$ 
51: end for=0

```
