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Synthesizing Robust Decentralized P2P Energy Trading Scheme with ‘n-1’ Contingency Analysis

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Billions of new energy devices generating energy from variable energy resources are difficult to manage centrally alone. As such, a decentralized power system is a defining feature of the ongoing energy transition development in the corporation of P2P energy trading scheme. A proper design of a decentralized P2P energy trading scheme enables optimal use of renewable energy, with consideration of the overall economic effectiveness. Nevertheless, proper energy planning regarding decentralized power supply management needs to be primed upfront. As the growing penetration of renewable energies increases power system instability, the impact of contingencies needs to be identified in the decentralized P2P energy trading scheme to enhance its reliability. The involved players need to ensure the reliability of the decentralized P2P energy trading scheme and have backup plans to make sure its normal performance can be met. N-1 contingency analysis proposed to synthesize a robust decentralized P2P energy trading scheme. In the illustrated case study, three different entities in P2P energy trading system are analyzed and their back-up plans are identified using N-1 contingency analysis. The results showed that the three entities need to have an excess renewables amount of 98 kWh, 87 kWh and 98 kWh in the case where one of them is having power outages to meet the desired performance. The generated outcomes not only provide a handy lens for the players involved but also for the decision-makers who wish to identify the risks that may occur in P2P energy trading scheme.

1. Introduction

The 27th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP27) was held against a backdrop of extreme weather events worldwide, an energy crisis propelled by the war in Ukraine, and scientific data reiterating that the world is not doing enough to tackle carbon emissions and protect the future of our planet (United Nations, 2022). According to scientists, global carbon dioxide emissions from burning fossil fuels are on track to rise around 1 % in 2022, making it harder for the world to avoid disastrous climate change impacts (Abnett, 2022). It was recognized that immediate actions are required to reduce global carbon emissions and mitigate the impacts of climate change.

Malaysia has the national goal of reaching 70 % of renewables in the power mix by 2050, which means that the nation is in the middle of a major energy transition from a fossil-based energy system to a more decentralized renewable energy system (Enerdata, 2023). One of the developments in this transition is the concept of P2P energy trading system, launched by the Sustainable Energy Development Authority (SEDA) in 2019 where prosumers can trade their excess electricity with other consumers or sell it back to the utility company (SEDA, 2020). On the other hand, the P2P energy trading model has been analyzed by Kong et al. (2022a) that P2P energy trading system not only can provide financial gains for the prosumers, achieving energy performance and meeting the carbon emissions goal and is believed that such model on micro-time basis deserves to be explored (Kong et al., 2022b). Another work from Liu et al. (2023), developed a novel P2P energy trading method

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that is based on data envelopment analysis that consists of a three-layer optimization model for building microgrids.

The efforts that had been done in optimizing P2P energy trading system are remarkable but only limited works had considered the resiliency of the P2P energy trading model. An admirable work from Rezaei and Ghasemi (2022), they had proposed a stochastic optimization framework in enhancing the resiliency of P2P energy trading system that involved hubs and energy storages during severe disturbance. Yet, so far, there has been no work utilizing N-1 contingency analysis that guarantees the energy and cost performance can be met simultaneously. Disturbances, like energy outages, can result in cascading outages leading to low energy performance, high electricity bills and failure to meet the carbon emissions goal. As the reliability of the energy system is the main concern for the prosumers and decision-makers, much work has been done in the contingency analysis area. For instance, Omran et al. (2016) conducted an N-1 contingency analysis in distributed series reactor technology to ensure secure operation during grid transmission. It has been proven that such N-1 contingency analysis is an essential tool in evaluating power system reliability by predicting the power system state disruption (Salami, 2017). With the aid of N-1 contingency analysis, the decision-makers or planning can effectively identify the possible contingencies and devise corresponding measures from a steady steady-state perspective (i.e., the power system should withstand any single component failure while supporting all the energy loads in the system). Therefore, the objective of this work is to conduct the N-1 contingency analysis for the P2P energy trading system and identify the optimal renewable capacity for all involved to ensure the desired performance of the P2P energy trading system can be met.

2. Problem statement

A hypothetical example is utilized to demonstrate the effectiveness of N-1 contingency analysis in enhancing the resiliency of the P2P energy trading scheme. The problem definition of P2P energy trading can be stated as follow: Given that three entities with different energy profiles are involved in the P2P energy trading scheme, namely Entity A, B and C. The time intervals of 30 min in a month are defined as $T = 1,2 \ldots N$. The energy demand of each interval is denoted as $D_T = \{D_1, D_2 \ldots D_N\}$. The energy of each time interval can be fulfilled by either fossil-based energy (S_F), self-generated renewable energy (S_R) or traded renewable energy from other entities ($S_{R'}$). Each energy source has its emission intensity, which they are denoted as CI_F and CI_R. Note that the self-generated renewables and traded renewables are using the same emission intensity since they are from the same source. In this particular work, the objective is to perform the N-1 contingency analysis in the P2P energy trading system by identifying the minimum renewable capacity required for each entity without affecting the overall cost performance.

3. Methodology

In the P2P energy trading scheme, the malfunction of renewable energy systems could lead to an overall higher electricity bill as more fossil-based energy sources would need to be utilized to compensate for the renewables. To account for the critical N-1 contingencies in the P2P energy trading scheme, the minimum renewables required for each entity can be determined by analyzing their cost performance. It should be noted that the minimum amount of renewables is considered optimal for the contingency analysis when the overall electricity bills are similar to the initial P2P energy trading scheme (where no disruption is encountered). Figure 1 shows the methodology flowchart proposed for the N-1 contingency analysis for P2P energy trading system.

For the first step, the optimal P2P energy trading model of the three entities is developed with the objective of minimizing total electricity bills and a pre-determined carbon emission reduction goal. Note that the model is developed without considering the resiliency of the P2P energy trading system (where one of the self-generated renewable systems is under disruption and could not supply renewable energy to itself or other partner entities). Therefore, the minimum capacity of renewables redundancy is required to be determined for each entity, so that the energy demand and minimum electricity bills can be achieved even when one of the entities is having disruption on its renewables system. N-1 contingency analysis is performed to determine the minimum renewables capacity required for all involved entities in the P2P energy trading system. Such analysis is conducted 3 times to capture all possible disruption scenarios. The analysis is conducted by increasing the renewable capacity of the other two partner entities by 10 kWh each until the overall electricity bill is similar to the case where no disruption occurs. The optimal renewables capacity of each entity can be determined by the maximum amount of renewables needed in different scenarios that achieve similar electricity bills as the initial one (where no disruption is occur in the P2P energy trading system). With this, one can ensure the P2P energy trading system can still operate at full capacity by achieving the desired energy performance and electricity bills.

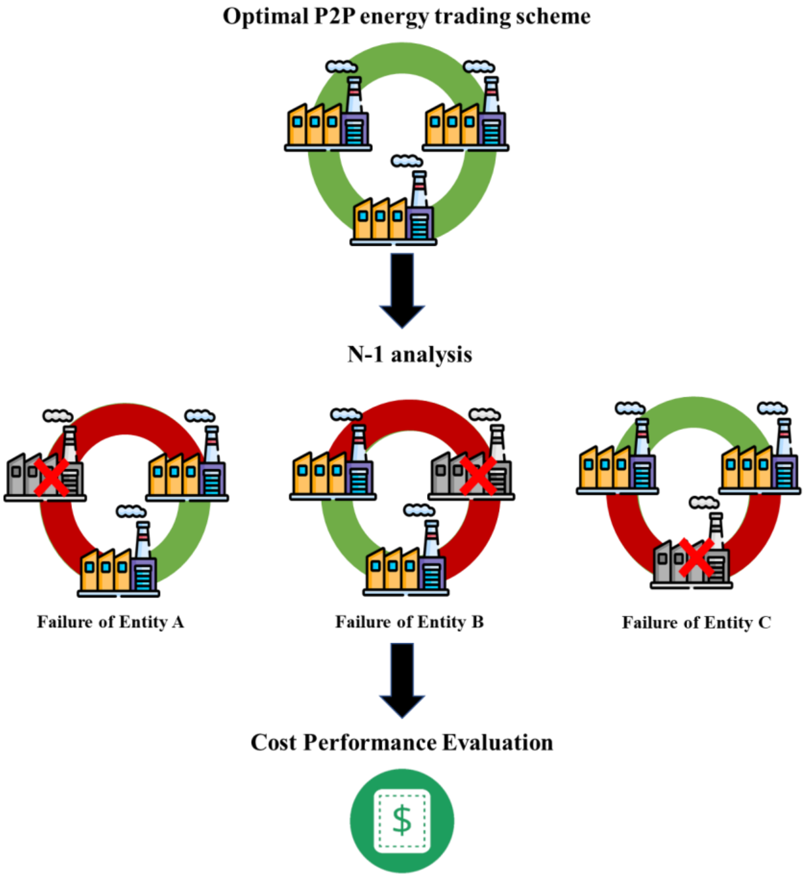

Figure 1: Methodology flowchart for N-1 contingency analysis in P2P energy trading scheme

4. Model formulation

The P2P energy trading model is an extension of the work conducted by Kong et al. (2022), in which the mentioned work does not consider the resiliency of the energy system. The model used in this case study is adapted to the actual billing system used in Malaysia but can be easily adapted to different costing mechanisms. Note that the equations formulated are modelled through mixed-integer linear programming (MILP) and can be solved using any programming software. For the first step, the minimum amount of renewables of each entity is determined to meet the carbon emission reduction. This is computed using Eq.(1), where $S_{Total\ Renewables}$ denotes the total renewables required across the one-month period, while $S_{R,T}$ and $S_{ER,T}$ refers to the amount of self-generated renewables and stored renewables applied to the system at time interval T.

$$MinS_{Total\ Renewables} = \sum_{T} (S_{R,T} + S_{ER,T}) \tag{1}$$

The initial carbon emission, E_i is presumed to be generated from fossil-based energy resources, where it can be expressed as Eq.(2). As for the carbon emission goal, E_G, can be mathematically expressed as Eq.(3) – Eq.(4), where ∂ is indicated as the carbon emission reduction ratio and is fulfilled by various energy sources and their respective carbon intensities.

$$E_{in} = \sum_{T} (S_{F,T} \times CI_F) \tag{2}$$

$$E_G = E_{in} \times (1 - \partial) \tag{3}$$

$$E_G = S_F CI_F + S_R CI_R + S_{ER} CI_R \tag{4}$$

The entity's energy demand can be fulfilled by different energy sources, including fossil-based energy sources, self-generated renewables or stored renewables (shown in Eq.(5)). Note that the self-generated renewables indicated in this case study are solar PV, so it can only be supplied to the energy system during day time.

$$D_T = \begin{cases} S_{F,T} + S_{R,T} + S_{ER,T}\big|_{Daytime} \\ \quad S_{F,T} + S_{ER,T}\big|_{Nightiime} \end{cases} \qquad \forall T \tag{5}$$

The above formulations are incorporated into a mixed-integer linear programming model and solved to obtain the minimum amount of renewables required for each entity to fulfil the pre-determined carbon emission goal. In the P2P energy trading system, the objective is to minimize the total electricity bills for all involved entities. When one of the entities has excess renewables, it can be traded to other entities to obtain an overall lower electricity bill. For the total electricity bill calculation $Cost_{Total,P}$, it can be expressed as Eq.(6), where $C_{T,P}$ indicates the normal electricity bill for that particular entity, C_{MD} is the maximum demand charge while $C_{TR,P}$ and $C_{TR,P'}$ denotes the traded renewables cost sold and buy from other players. The normal electricity bill, C_T can be presented as Eq.(7), where CF_F and CF_R are the cost factor of fossil-based energy sources and renewables. The maximum demand charges, C_{MD}, can be determined by diving the summation of fossil-based energies ($\sum_{T\in Peak} S_{F,T}$) in peak periods to the number of peak time intervals ($\sum_{T\in Peak} T$) and multiplying it by the cost factor of maximum demand (as shown in Eq.(8)). The traded renewables cost $C_{TR,P}$ and $C_{TR,P}{}'$ can be mathematically expressed as Eq.(9) and Eq.(10), where CF_{TR} is the renewables trade unit cost. The index P in the below equations refers to the entity indicated while P' represents other entities.

$$Min \sum_P Cost_{Total,p} = \sum_T C_{T,P} + \sum_P C_{MD} + \sum_P C_{TR,P} - \sum_{P'} C_{TR,P'} \tag{6}$$

$$C_T = \left(S_{F,T} CF_F\right) + \left(S_{R,T} CF_R\right) \qquad \forall T \tag{7}$$

$$C_{MD} = \frac{\sum_{T\in Peak} S_{F,T}}{\sum_{T\in Peak} T} \times CF_{MD,Peak} \tag{8}$$

$$C_{TR,P} = \sum_T (S_{TR,T,P} \times CF_{TR}) \tag{9}$$

$$C_{TR,P'} = \sum_T (S_{TR,T,P'} \times CF_{TR}) \tag{10}$$

The energy demand expression in P2P energy trading system is revised as Eq.(9) and Eq.(10), in which traded renewables ($S_{TR,T,P'}$) are incorporated into the equation.

$$D_{T,P} = \begin{cases} S_{F,T,P} + S_{R,T,P} + S_{ER,T} + S_{TR,T,P'}\big|_{Daytime} \\ \quad S_{F,T,P} + S_{ER,T,P} + S_{TR,T,P'}\big|_{Nightiime} \end{cases} \qquad \forall T \tag{5}$$

5. Case study

To illustrate the application of N-1 contingency analysis in a P2P energy trading system, a hypothetical sample of three entities with different energy profiles in Malaysia is adopted as a case study in this work. Note that the billing system used in this particular is tabulated as Table 1.

Table 1: Cost Factor for each time interval (Tenaga Nasional Berhad-(2014)Tariff E3 High Voltage Peak/Off-Peak Industrial Tariff)

Time (h)	Classification	Cost factor (MYR/kWh)	Maximum Demand Charges (MYR/kW)	Cost Factor of Renewables (MYR/kWh)	Trade Unit Cost of Renewables (MYR/kWh)
00:00-08:00	Off Peak	0.202	0.00	0.25	0.275
08:00-22:00	Peak	0.337	35.50	0.25	0.275
22:00-00:00	Off-Peak	0.202	0.00	0.25	0.275

6. Results and discussion

In this work, the electricity bills for the N-1 contingency analysis are determined through the equations formulated in the former section. The initial electricity bill for the P2P energy trading system, where no disruption occurs in the renewables system, serves as the benchmark for this case study. Note that overall electricity bills for the involved entities are the main focus of this work, so the carbon emissions during the contingency are not significantly crucial and therefore not presented. In the case where no energy disruption occurs, the overall electricity bill is found to be MYR 248,890.20 with a 40 % of carbon emission reduction (shown in Table 2) and the results of the N-1 contingency analysis for the P2P energy trading system are shown in Figure 2.

Table 2: Initial electricity bill for all entities in the P2P energy trading system

Entity	Renewables used per month (kWh)	Renewables used per time interval (kWh)	Electricity bill (MYR)
A	138,627	186.33	86,452
B	111,444	149.79	76,384
C	138,843	186.62	86,145

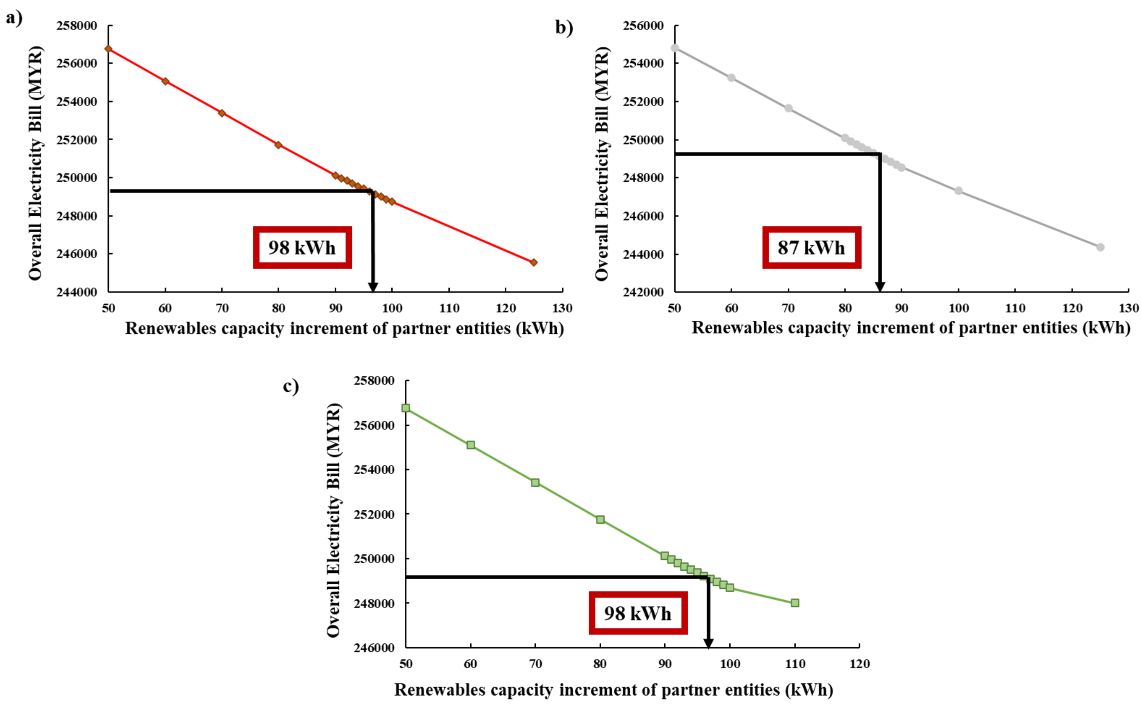

Figure 2: N-1 Contingency analysis results for a) Entity A; b) Entity B and c) Entity C

In the case where Entity A is assumed to have power disruption on its renewable energy system, the optimal renewable capacity increment for partner entities is determined as 98 kWh each. Therefore, Entity B and C need to increase their self-generated renewables capacity up to 247.79 kWh and 284.62 kWh. With this increment, the overall electricity bill is calculated to be MYR 249,011.68, only a MYR 30.88 (0.012 %) difference as compared to the full performance of the P2P energy trading system. On the other hand, in the next scenario, where Entity B is not generating any renewables, the optimal renewables capacity for Entity A and C is found to be 273.33 kWh and 273.62 kWh. The electricity bills for Entity A, B and C with this proposed renewable capacity are determined as MYR 79.701.80, MYR 89,888.20 and MYR 79,392.72. Note that even though Entity B need to pay an extra MYR 13,504.54, the overall electricity bill can still achieve up to MYR 248,982.71, which is only MYR 1.91 (0.00076 %) difference as compared to the initial condition. In the next case which Entity C has self-generated renewable system failure, 98 kWh of renewable capacity increment for Entity A and B is recommended. With the proposed renewables capacity, the electricity bill of Entity A, B and C is determined to be MYR 79,199.40, MYR 67,794.52 and MYR 101,958.17 individually. By looking at the results for the N-1 contingency analysis in the P2P energy trading system, in the case where the entity is having power disruption, it would still need to pay extra to achieve the minimum overall electricity bill. The proposed N-1 contingency plan utilized in the energy system allows the involved entities to have a backup plan to meet their desired performance goal in terms of cost. Instead of eliminating the disrupted entity, it is proposed to have the backup renewable capacity to enhance the resiliency of the P2P energy trading system and achieve the initial cost minimization goal.

7. Conclusions

The work evaluates the use of N-1 contingency analysis in a P2P energy trading system. In the case study with three different entities involved, three scenarios are modelled and analyzed. In this particular case study, the optimal increment of renewables capacity for all entities is proposed to be 98 kWh each to achieve the intended electricity bill. With the developed P2P energy trading model, along with the research and simulations conducted, the N-1 contingency analysis allows the energy system to enhance its resiliency and reliability of P2P energy trading system. It is believed that with the aid of the N-1 contingency plan, a positive impact is anticipated and move towards achieving a sustainable energy transition. Note that the indicated work only considers single-component failure in a 3-unit-power planning system. This work can be extended by having multiple objectives (carbon emissions goal, cost performance) N-1 contingency analysis or N-k analysis in a large P2P energy trading scheme.

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