Appendix I

Linearized power flow model

The AC power flow model in polar form for a power system with N^B buses is given by:

$$P_k = \sum_{r=1}^{N^B} G_{kr} V_k V_r cos\theta_{kr} + \sum_{r=1}^{N^B} B_{kr} V_k V_r sin\theta_{kr} \tag{I.1}$$

$$Q_k = -\sum_{r=1}^{N^B} B_{kr} V_k V_r cos\theta_{kr} + \sum_{r=1}^{N^B} G_{kr} V_k V_r sin\theta_{kr} \tag{I.2}$$

$$k = 1, 2, ..., N^B$$

Here $Y = (G + jB)$ represents the admittance of the power system. Also, without shunt elements, this admittance is represented as $Y' = (G' + jB')$. In real power systems, the magnitude of bus voltage for most scenarios is approximately 1 p.u. The absolute value of phase angle differences across lines seldom surpasses 30° [86], and the majority of them are within 10° [87]. Also, the admittance matrix of the power system is represented as

$$Y_{kr} := \begin{cases} -y_{kr}, & \text{if } k \neq r \\ y_{kk} + \sum_{s=1, s\neq k}^{N^B} y_{k,s} & \text{if } k = r. \end{cases} \tag{I.3}$$

The shunt element represents the contribution of shunt capacitors, the line-charging susceptance, and the equivalent admittance of transformers and phase shifters. By taking into account these informations, the linear approximations are applied to I.1 for decoupling the voltage magnitudes and the phase angles as follows.

$$P_k = \sum_{r=1}^{N^B} G_{kr} V_k V_r cos\theta_{kr} + \sum_{r=1}^{N^B} B_{kr} V_k V_r sin\theta_{kr} \tag{I.4}$$

$$= g_{kk}V_k^2 + \sum_{r=1,r\neq k}^{N^B} g_{kr}V_k^2 - \sum_{r=1,r\neq k}^{N^B} g_{kr}V_kV_r cos\theta_{kr} - \sum_{r=1,r\neq k}^{N^B} b_{kr}V_kV_r sin\theta_{kr} \tag{I.5}$$

$$= g_{kk}V_k^2 + \sum_{r=1,r\neq k}^{N^B} (g_{kr}V_k(V_k - V_r cos\theta_{kr}) - b_{kr}V_kV_r sin\theta_{kr}) \tag{I.6}$$

The term $g_{kr}V_k(V_k - V_r cos\theta_{kr})$ in equation (I.6) can be approximated to $g_{kr}(V_k - V_r)$ as proposed in [88]. Considering this and the facts described earlier, equation (I.6) can be re-written in approximated form as follows.

$$P_k \approxeq g_{kk}V_k + \sum_{r=1,r\neq k}^{N^B} g_{kr}(V_k - V_r) - \sum_{r=1,r\neq k}^{N^B} b_{kr}(\theta_k - \theta_r) \tag{I.7}$$

$$= \left(V_k \sum_{r=1}^{N^B} g_{kr} + \sum_{r=1,r\neq k}^{N^B} (-g_{kr})V_r \right) - \left(\theta_k \sum_{r=1,r\neq k}^{N^B} b_{kr} + \sum_{r=1,r\neq k}^{N^B} (-b_{kr})\theta_r \right) \tag{I.8}$$

$$= \sum_{r=1}^{N^B} G_{kr}V_r - \sum_{r=1}^{N^B} {B'}_{kr}\theta_r \tag{I.9}$$

Similarly, the reactive power from equation (I.2) can also be approximated as follows.

$$Q_k = -\sum_{r=1}^{N^B} B_{kr}V_r - \sum_{r=1}^{N^B} {G'}_{kr}\theta_r \tag{I.10}$$

The average branch flow can also be obtained from all these equations as follows.

$$P_{kr} = g_{kr}(V_k - V_r) - b_{kr}(\theta_k - \theta_r) \tag{I.11}$$

$$Q_{kr} = -b_{kr}(V_k - V_r) - g_{kr}(\theta_k - \theta_r) \tag{I.12}$$

Using equations (I.9) and (I.10), the power flow equations can be written in matrix form as follows

$$\begin{bmatrix} P \\ Q \end{bmatrix} = - \begin{bmatrix} B' & -G \\ G' & B \end{bmatrix} \begin{bmatrix} \theta \\ V \end{bmatrix} \tag{I.13}$$

Using the equation I.9, the active power balance equations for optimal flow can be derived as follows.

$$\sum_{k=1}^{N^B} P_k = \sum_{k=1}^{N^B}\sum_{r=1}^{N^B} G_{kr}V_r - \sum_{k=1}^{N^B}\sum_{r=1}^{N^B} {B'}_{kr}\theta_r \tag{I.14}$$

$$= \sum_{r=1}^{N^B} (\sum_{k=1}^{N^B} G_{kr}) V_r - \sum_{r=1}^{N^B} (\sum_{k=1}^{N^B} B'_{kr}) \theta_r \tag{I.15}$$

$$= \sum_{r=1}^{N^B} (\sum_{k=1}^{N^B} G_{kr}) V_r = \sum_{r=1}^{N^B} (g_{rr}) V_r = \sum_{r=1}^{N^B} g_{rr} \tag{I.16}$$

The approximation is done in equation I.16 because $V_r \approx 1$ which follows the following approximation.

$$\sum_{k=1}^{N^B} P_k = \sum_{r=1}^{N^B} g_{rr} V_r \approx \sum_{r=1}^{N^B} g_{rr} V_r^2 \approx \sum_{r=1}^{N^B} g_{rr} \tag{I.17}$$

In the real power system, the conductance of the ground branches is extremely small, which results in the sum of the injected active power close to zero. The active power balance equation can be written as follows.

$$\sum_{k=1}^{N^B} P_k = 0 \tag{I.18}$$

Similarly, the reactive power balance equation, i.e., the sum of injected reactive power,r, can be written as follows.

$$\sum_{k=1}^{N^B} Q_k = -\sum_{r=1}^{N^B} b_{rr} V_r \approx -\sum_{r=1}^{N^B} b_{rr} V_r^2 \approx -\sum_{r=1}^{N^B} b_{rr} \tag{I.19}$$

Generation Shift Distribution Factors

For the calculation of LMPs in the work, generation shift distribution (GSF) factors are used as in ref. [81]. For this, the linear model developed in previous section is used. From I.13, let U be a singular matrix, such that,

$$U = \begin{bmatrix} B' & -G \\ G' & B \end{bmatrix} \tag{I.20}$$

The row and coloumn corresponding to the reference bus is removed from this singular matrix U to make U^a which is a invertible matrix. Thus,

$$\begin{bmatrix} \theta' \\ V \end{bmatrix} = -U^{a-1} \begin{bmatrix} P' \\ Q \end{bmatrix}. \tag{I.21}$$

Here, U^{a-1} is inverse of U^a and (θ', P') are (θ, P) respectively with reference bus removed. For appropriateness, the row and column of the reference bus of the matrix $-U^{a-1}$ are occupied by zeros to obtain a new matrix X with the dimension of $2N^B \times 2N^B$. Therefore we can write equation (I.21) as follows.

$$\begin{bmatrix} \theta \\ V \end{bmatrix} = X \begin{bmatrix} P \\ Q \end{bmatrix}. \tag{I.22}$$

Equation (I.22) can be used for the calculation of bus voltage. The voltage magnitude and phase angle at bus k are respectively given by,

$$V_k = \sum_{k'=1}^{N^B} X_{N^B+k,k'} P_{k'} + \sum_{k'=1}^{N^B} X_{N^B+k,N^B+k'} Q_{k'}, \qquad and \tag{I.23}$$

$$\theta_k = \sum_{k'=1}^{N^B} X_{k,k'} P_{k'} + \sum_{k'=1}^{N^B} X_{k,N^B+k'} Q_{k'}. \tag{I.24}$$

The equations (I.23) and (I.24) can be substituted in equations (I.11) and (I.12) as shown below.

$$\begin{aligned} P_{kr} = & \sum_{k'=1}^{N^B} \left(g_{kr}(X_{N^B+k,k'} - X_{N^B+r,k'}) - b_{kr}(X_{k,k'} - X_{r,k'}) \right) P_{k'} + \\ & \sum_{k'=1}^{N^B} \left(g_{kr}(X_{N^B+k,N^B+k'} - X_{N^B+r,N^B+k'}) - b_{kr}(X_{k,N^B+k'} - X_{r,N^B+k'}) \right) Q_{k'} \end{aligned} \tag{I.25}$$

$$\begin{aligned} Q_{kr} = & \sum_{k'=1}^{N^B} \left(-g_{kr}(X_{k,k'} - X_{r,k'}) - b_{kr}(X_{N^B+k,k'} - X_{N^B+r,k'}) \right) P_{k'} + \\ & \sum_{k'=1}^{N^B} \left(-g_{kr}(X_{k,N^B+k'} - X_{r,N^B+k'}) - b_{kr}(X_{N^B+k,N^B+k'} - X_{N^B+r,N^B+k'}) \right) Q_{k'} \end{aligned} \tag{I.26}$$

Using equation (I.25) and (I.26), the generation shift distribution factor ($f_{l-k'}$) from bus k' to line l between bus k and r can be defined as follows.

- $f_{l-k'}^{P-P}$=the GSD factor from the active power generation at bus k' to the active power flow across line $l = g_{kr}(X_{N^B+k,k'} - X_{N^B+r,k'}) - b_{kr}(X_{k,k'} - X_{r,k'})$
- $f_{l-k'}^{P-Q}$=the GSD factor from the reactive power generation at bus k' to the active power flow across line $l = g_{kr}(X_{N^B+k,N^B+k'} - X_{N^B+r,N^B+k'}) - b_{kr}(X_{k,N^B+k'} - X_{r,N^B+k'})$
- $f_{l-k'}^{Q-P}$=the GSD factor from the active power generation at bus k' to the reactive power flow across line $l = -g_{kr}(X_{k,k'} - X_{r,k'}) - b_{kr}(X_{N^B+k,k'} - X_{N^B+r,k'})$

- $f^{Q-Q}_{l-k'}$=the GSD factor from the reactive power generation at bus k' to the reactive power flow across line $l = -g_{kr}(X_{k,N^B+k'} - X_{r,N^B+k'}) - b_{kr}(X_{N^B+k,N^B+k'} - X_{N^B+r,N^B+k'})$

These GSD factors make the calculation of LMPs simple and thus, are used in this work for the same.

Appendix II

Modified IEEE 33-bus distribution system data

The IEEE-33 bus system is modified to include the DG and Virtual community for the system studies presented in this thesis. The single-line diagram of the modified IEEE 33-bus distribution system is depicted in Figure II.1. The line data, load data and type of customers connected at different buses are presented in Table II.1 [89].

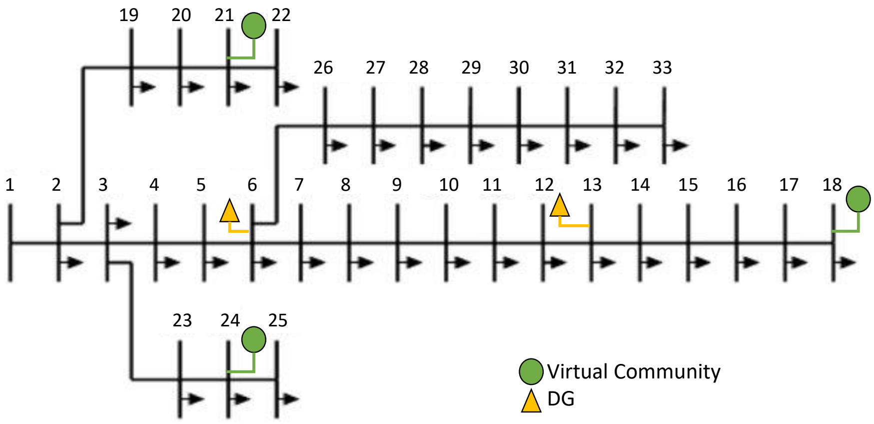

Figure II.1: Modified IEEE 33-bus distribution system

Table II.1: MODIFIED IEEE 33-BUS DISTRIBUTION SYSTEM DATA

Bus[1]		r (ohm)	x (ohm)	TB Load		Type[2]
FB	TB			P (kW)	Q (kVAR)	
1	2	0.0922	0.047	100	60	R
2	3	0.493	0.2511	90	40	I
3	4	0.366	0.1864	120	80	C
4	5	0.3811	0.1941	60	30	R
5	6	0.819	0.707	60	20	I
6	7	0.1872	0.6188	200	100	C
7	8	0.7114	0.2351	200	100	C
8	9	1.03	0.74	60	20	I
9	10	1.044	0.74	60	20	C
10	11	0.1966	0.065	45	30	C
11	12	0.3744	0.1238	60	35	R
12	13	1.468	1.155	60	35	C
13	14	0.5416	0.7129	120	80	R
14	15	0.591	0.526	60	10	C
15	16	0.7463	0.545	60	20	I
16	17	1.289	1.721	60	20	C
17	18	0.732	0.574	90	40	I
2	19	0.164	0.1565	90	40	R
19	20	1.5042	1.3554	90	40	C
20	21	0.4095	0.4784	90	40	I
21	22	0.7089	0.9373	90	40	R
3	23	0.4512	0.3083	90	50	C
23	24	0.898	0.7091	420	200	C
24	25	0.896	0.7011	420	200	C
6	26	0.203	0.1034	60	25	C
26	27	0.2842	0.1447	60	25	I
27	28	1.059	0.9337	60	20	C
28	29	0.8042	0.7006	120	70	C

Table II.1: Modified IEEE 33-bus distribution system data

Bus[1]		r (ohm)	x (ohm)	TB Load		Type[2]
FB	TB			P (kW)	Q (kVAR)	
29	30	0.5075	0.2585	200	600	C
30	31	0.9744	0.963	150	70	R
31	32	0.3105	0.3619	210	100	R
32	33	0.341	0.5302	60	40	C

[1]FB- From bus, TB- To bus; [2]C- Commercial, I- Industrial, R- Residential

The real time digital simulator (RTDS) is also used in this study. The workstation used with RTDS is shown in Figure II.2.

Figure II.2: Image showing RTDS connected to Work Station

The respective modified IEEE 33 bus distribution model is present in Figure II.3.

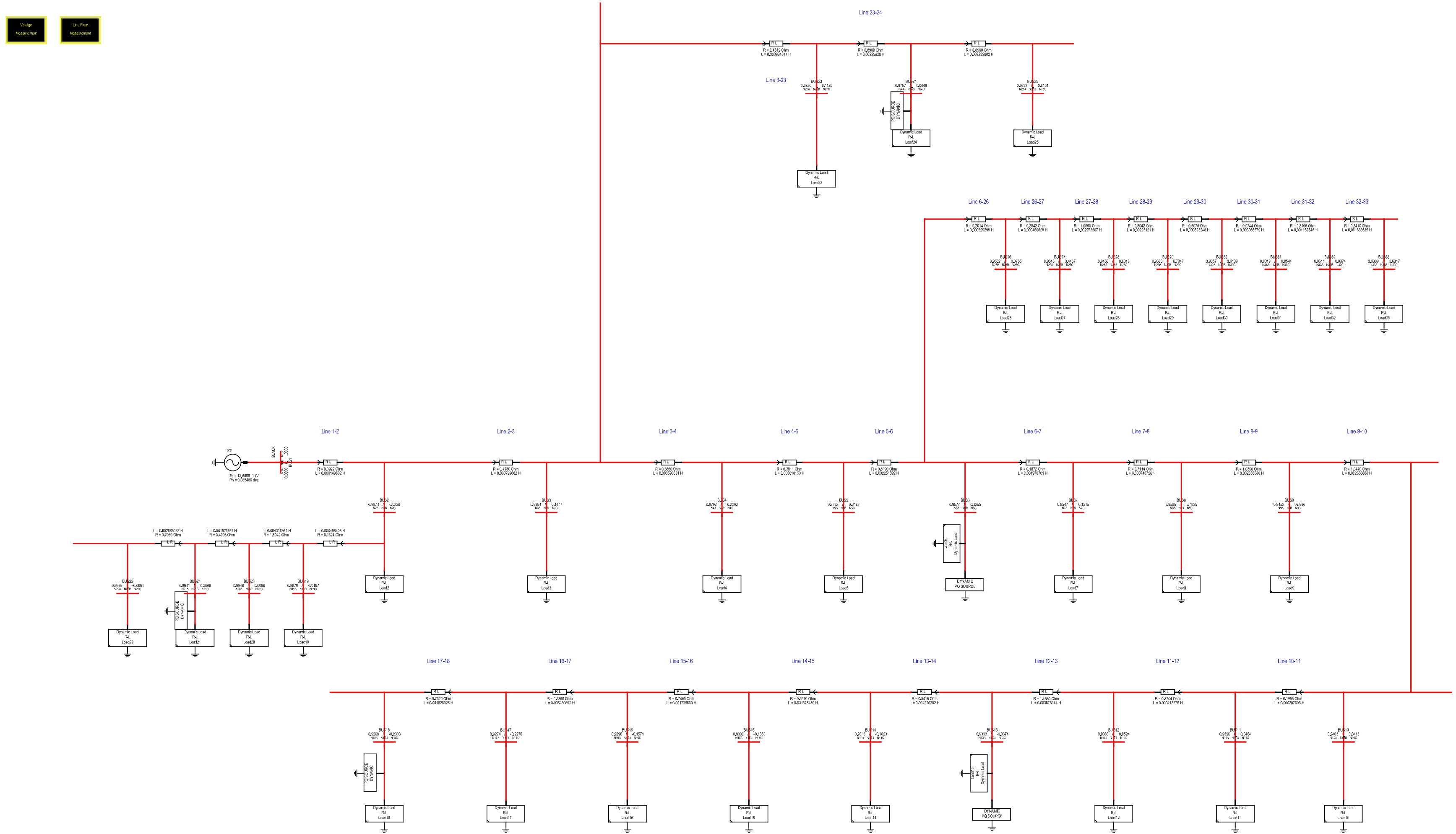

Figure II.3: RSCAD MODEL OF MODIFIED IEEEE 33-BUS SYSTEM

Appendix III

Modification of the optimization problem

In the proposed framework, the minimization of the objective function, for instance, can be written in the following way for the virtual community.

$$C^c = \sum_{t=1}^{T} \left(\Lambda_t^{im} P_t^b - \Lambda_t^{ex} P_t^s + \Lambda^{UTI} (P_t^{ch} + P_t^{dis}) \right). \tag{III.27}$$

Here, P_t^b and P_t^s are the power bought (imported) and sold (exported) from the utility. The prices of power import and export are given by Λ_t^{im} and Λ_t^{ex}, respectively. The charging and discharging power profile is given by P_t^{ch} and P_t^{dis}, respectively. The battery utilization coefficient is given by Λ^{UTI}. The constraints associated with the above equations are as follows.

$$-P_t^{ch} \leq 0, \qquad : \mu_t^1 \tag{III.28}$$

$$P_t^{ch} - P^{ch_{max}} \leq 0, \qquad : \mu_t^2 \tag{III.29}$$

$$-P_t^{dis} \leq 0, \qquad : \mu_t^3 \tag{III.30}$$

$$P_t^{dis} - P^{dis_{max}} \leq 0, \qquad : \mu_t^4 \tag{III.31}$$

$$SOC_t - (1 - \eta^{loss}) SOC_{t-1} - \eta^{ch} P_t^{ch} + \frac{1}{\eta^{dis}} P_t^{dis} = 0, \qquad : \lambda_t^1 \tag{III.32}$$

$$SOC^{min} - SOC_t \leq 0, \qquad : \mu_t^5 \tag{III.33}$$

$$SOC_t - SOC^{max} \leq 0, \qquad : \mu_t^6 \tag{III.34}$$

$$P_t^b - P_t^s + P_t^{dis} - P_t^{ch} - P_t^l = 0. \qquad : \lambda_t^2 \tag{III.35}$$

$$-P_t^b \leq 0, \qquad : \mu_t^7 \tag{III.36}$$

$$-P_t^s \leq 0, \qquad : \mu_t^8 \tag{III.37}$$

The limits on charging and discharging power profiles are given by (III.28,III.29,III.30,III.31). The next stage SOC and its limit are given by (III.32,III.33,III.34). The load balancing equation is given by (III.35), where P_t^l is the total load demand of the virtual community. The limits on utility import and export in given by equations (III.36) and (III.37).

The Lagrangian L for this problem is:

$$L = C^c + \sum_{t=1}^{T} \left(\mu_t^1(0 - P_t^{ch}) + \mu_t^2(P_t^{ch} - P^{ch_{max}}) + \mu_t^3(0 - P_t^{dis}) + \mu_t^4(P_t^{dis} - P^{dis_{max}})\right)$$

$$+ \sum_{t=1}^{T} \lambda_t^1 \left(SOC_t - (1 - \eta^{loss})SOC_{t-1} - \eta^{ch} P_t^{ch} + \frac{1}{\eta^{dis}} P_t^{dis} \right)$$

$$+ \sum_{t=1}^{T} \left(\mu_t^5(SOC^{min} - SOC_t) + \mu_t^6(SOC_t - SOC^{max})\right)$$

$$+ \sum_{t=1}^{T} \lambda_t^2 \left(P_t^b - P_t^s + P_t^{dis} - P_t^{ch} - P_t^l\right) + \sum_{t=1}^{T} \left(\mu_t^7(0 - P_t^b) + \mu_t^8(0 - P_t^s)\right).$$

The KKT conditions for this problem are as follows.

- Stationarity

1.With respect to P_t^b:

$$\frac{\partial L}{\partial P_t^b} = \Lambda_t^{im} + \lambda_t^2 - \mu_t^7 = 0 \tag{III.38}$$

2. With respect to P_t^s:

$$\frac{\partial L}{\partial P_t^s} = -\Lambda_t^{ex} - \lambda_t^2 - \mu_t^8 = 0 \tag{III.39}$$

3. With respect to P_t^{ch}:

$$\frac{\partial L}{\partial P_t^{ch}} = \Lambda^{UTI} - \mu_t^1 + \mu_t^2 - \lambda_t^1 \eta^{ch} - \lambda_t^2 = 0 \tag{III.40}$$

4. With respect to P_t^{dis}:

$$\frac{\partial L}{\partial P_t^{dis}} = \Lambda^{UTI} - \mu_t^3 + \mu_t^4 + \frac{\lambda_t^1}{\eta^{dis}} + \lambda_t^2 = 0 \tag{III.41}$$

5. With respect to SOC_t:

$$\frac{\partial L}{\partial SOC_t} = \lambda_t^1 - \lambda_{t+1}^1 - \mu_t^5 + \mu_t^6 = 0 \tag{III.42}$$

- Primal Feasibility

  Each of the constraints must hold for the optimal solution:

$$0 - P_t^{ch} \leq 0, \quad P_t^{ch} - P^{ch_{max}} \leq 0$$

$$0 - P_t^{dis} \leq 0, \quad P_t^{dis} - P^{dis_{max}} \leq 0$$

$$SOC^{min} - SOC_t \leq 0, \quad SOC_t - SOC^{max} \leq 0$$

$$SOC_t = (1 - \eta_n^{loss})SOC_{n,t-1} + \eta_n^{ch} P_t^{ch} - \frac{1}{\eta_n^{dis}} P_t^{dis}$$

$$P_t^b - P_t^s + P_t^{dis} - P_t^{ch} - P_t^l = 0$$

$$0 - P_t^b \leq 0, \quad 0 - P_t^s \leq 0 \leq 0$$

- Dual Feasibility

  All Lagrange multipliers for inequality constraints must be non-negative:

$$\mu_t^1, \mu_t^2, \mu_t^3, \mu_t^4, \mu_t^5, \mu_t^6, \mu_t^7, \mu_t^8 \geq 0$$

- Complementary Slackness

  For each inequality constraint, the product of the Lagrange multiplier and the constraint must be zero:

$$\mu_t^1(0 - P_t^{ch}) = 0, \quad \mu_t^2(P_t^{ch} - P^{ch_{max}}) = 0$$

$$\mu_t^3(0 - P_t^{dis}) = 0, \quad \mu_t^4(P_t^{dis} - P^{dis_{max}}) = 0$$

$$\mu_t^5(SOC^{min} - SOC_t) = 0, \quad \mu_t^6(SOC_t - SOC^{max}) = 0$$

$$\mu_t^7(0 - P_t^b) = 0, \quad \mu_t^8(0 - P_t^s) = 0$$

These are the full KKT conditions, and solving these equations simultaneously yields the optimal solution for both the primal and dual problems.

Now, we will take two assumptions and check whether they are true or false.

- **Assumption 1:** Both the imported, P_t^b, and exported power, P_t^s, is non-zero simultaneously at any time t.

  Using this assumption and the condition for complementary slackness, we get $\mu_t^7 = 0$ and $\mu_t^8 = 0$. These values can be used in equations (III.38) and (III.38) to get the following equation.

$$\lambda_t^2 = -\Lambda_t^{im} = \Lambda_t^{ex} \tag{III.43}$$

This is not possible as the price of import and price of export both will be positive and will differ in value in the proposed framework. Thus, our assumption of both the imported, P_t^b, and exported power, P_t^s, is non-zero simultaneously at any time t is false.

- **Assumption 2:** Both the charging, P_t^{ch}, and discharging power, P_t^{dis}, is non-zero simultaneously at any time t.
  It is also assumed that they are under their upper limits. Using these assumptions and the condition for complementary slackness, we get $\mu_t^1 = 0$, $\mu_t^2 = 0$, $\mu_t^3 = 0$, and $\mu_t^4 = 0$. These values can be used in equations (III.40) and (III.41) to get the following equation.

$$\lambda_t^2 = \Lambda^{UTI} - \lambda_t^1 \eta^{ch} = -\Lambda^{UTI} - \lambda_t^1 \frac{1}{\eta^{dis}} \tag{III.44}$$

To assess this, we need to consider other stationarity conditions.

1. If $P_t^b > 0$, then due to the condition of complementary slackness $\mu_t^7 = 0$ and from equation (III.38), $\lambda_t^2 = -\Lambda_t^{im}$. Thus, equation (III.44) is modified as follows.

$$-\Lambda_t^{im} = \Lambda^{UTI} - \lambda_t^1 \eta^{ch} = -\Lambda^{UTI} - \lambda_t^1 \frac{1}{\eta^{dis}} \tag{III.45}$$

   This equation can be re-written as follows.

$$\lambda_t^1 = \frac{\Lambda_t^{im} + \Lambda^{UTI}}{\eta^{ch}} = \eta^{dis}(\Lambda_t^{im} - \Lambda^{UTI}) \tag{III.46}$$

2. If $P_t^s > 0$, then due to the condition of complementary slackness $\mu_t^8 = 0$ and from equation (III.38), $\lambda_t^2 = \Lambda_t^{ex}$. Thus, equation (III.44) is modified as follows.

$$\Lambda_t^{ex} = \Lambda^{UTI} - \lambda_t^1 \eta^{ch} = -\Lambda^{UTI} - \lambda_t^1 \frac{1}{\eta^{dis}} \tag{III.47}$$

   This equation can be re-written as follows.

$$\lambda_t^1 = \frac{-\Lambda_t^{ex} + \Lambda^{UTI}}{\eta^{ch}} = \eta^{dis}(-\Lambda_t^{ex} - \Lambda^{UTI}) \tag{III.48}$$

Even if we assume $\eta^{ch} = \frac{1}{\eta^{dis}}$, then also, equation (III.46) and (III.48) will not give a common value for λ_t^1. Thus, our assumption of both the charging, P_t^{ch}, and discharging power, P_t^{dis}, is non-zero simultaneously at any time t is false.

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List of Publications

<u>**Journal**</u>

1. **Mishra, M.**, Singh, A., Misra, R. K., Singh, D., & Maulik, A. (2023). A Scalable and Computational Efficient Peer-to-Peer Energy Management Scheme. *IEEE Access*, 11, 21686-21698.

2. **Mishra, M.**, Singh, A., Misra, R. K., & Singh, D. (2023). Peer-to-Peer Energy Trading with Active Participation of Distributed Generation. *IEEE Internet of Things Journal*, 10(23), 21076-21088.

3. **Mishra, M.**, Singh, A., Misra, R. K., Singh, D., & Maulik, A. (2024) Enhancing network-constrained P2P energy sharing through virtual communities. *Sustainable Energy, Grids and Networks*: 101276.

4. **Mishra, M.**, Singh, A., Misra, R. K., & Singh, D. (2024). Two-Tier Peer-to-Peer Transactive Energy Market. I *IEEE Transactions on Industry Applications*.

Conference

1. **Mishra, M.**, Singh, A., Misra, R. K., & Singh, D. (2022, December). Stochastic Peer-to-Peer Energy Trading with Price and Incentive Mechanism. In 2022 22nd National Power Systems Conference (NPSC) (pp. 761-766). IEEE.

2. **Mishra, M.**, Singh, A., Misra, R. K., & Singh, D. (2023, June). Virtual Community based Peer-to-Peer Energy Trading. In 2023 5th International Conference on Energy, Power and Environment (ICEPE) (pp. 1-6). IEEE.

To,
The DEAN (Academic Affairs)
IIT (BHU), Varanasi

Subject: Ph.D. thesis of Monika Mishra

Dear Sir,

I have received the comments of the examiners on my thesis entitled "Peer-to-peer Energy Transactions in Active Distribution Network: A Game-theoretic Approach" on 28^{th} Jan 2025.

I went through all the comments and made appropriate corrections in the thesis taking care of all the points mentioned in the comments forwarded to me. The received comments have been reproduced in the response letter for better clarity.

Please find responses that describe how comments are incorporated into the thesis.

With kind regards,
Yours sincerely

Monika Mishra
Roll No. 20081001
Research Scholar
Department of Electrical Engineering

Encl:
1. Comments as received
2. Responses on the comments received
3. Four copies of the thesis after incorporating the corrections (the corrections are flagged in one copy).

Response to the comments received

Candidate expresses his sincere gratitude towards the examiners for sparing their precious time to evaluate the thesis and to make valuable comments, suggestions, and criticism. Candidate has carefully addressed all the comments and made corresponding changes in the revised version of the thesis. Candidate believes that these modifications lead to significant additions and improvements in the thesis and the four copies of the revised thesis.

For clarity in reading, we have followed the following procedure while responding to the examiners' comments.
(a) The examiners' comments are enclosed in a box so that it is clearly visible.
(b) Our responses are in black color font following the examiners' comments.
(c) The modifications in the thesis are given in blue font color.

Examiner 1

List of points for clarification:

1: For the game-theoretic models presented in the thesis, the candidate is advised to elaborate on the assumptions made in the Nash Bargaining and Kalai-Smorodinsky models. How does the choice of game-theoretic approach affect compuational complexity?

Response: The candidate thanks the examiner for this comment as it enhances the quality of the thesis. For the game-theoretic model presented in the thesis, following assumptions[1] were made.

- Agreement: In cooperative game theory, it is assumed that players engage in discussions or negotiations before the game begins, leading to a formal agreement among all participants. This assumption ensures that players can coordinate their strategies to achieve mutually beneficial outcomes. Conversely, in non-cooperative games, it is assumed that no binding agreements are made before the game starts, and each player acts independently to maximize their own payoff.
- Reliable Communication Infrastructure: The models in this study assume that the communication channels used by players are robust, free from disruptions, and do not introduce delays. This ensures that information exchange between players occurs seamlessly, which is crucial in strategic decision-making processes.

[1] Petrus Eduardus Maria Borm. *On game theoretic models and solution concepts.* [Sl: sn], 1990.

- Rational Player Behavior: It is assumed that all players behave rationally, meaning they make decisions that maximize their expected utility based on the available information. The possibility of irrational behavior, such as decision-making influenced by emotions or biases, is not considered in this study..
- Multiple Strategies for Each Player: Each player in the game is assumed to have access to multiple strategic choices. This ensures that the game captures a wide range of possible interactions and outcomes rather than being restricted to a limited set of actions.
- Common Knowledge: All players are aware of the game's rules, possible strategies, and payoffs, and they also know that all other players have this knowledge.
- Static Virtual Community Formation: The virtual community structure remains fixed during the optimization period, without considering dynamic adjustments based on changing conditions.

The choice of a game-theoretic approach significantly impacts computational complexity, as different models require varying levels of computational resources to find equilibria or optimal strategies. When a large number of players are involved communication and computation complexity issues arises.[2] To reduce these complexities, in this thesis, the players (i.e. prosumers or buildings) have been grouped into virtual communities and Peer-to-peer (P2P) energy trading is divided into B2B (building-to-building), B2C (building-to-community) and C2C (community-to-community) energy trading. The computational complexity associated with some well-known game-theoretic approaches is outlined below.

- Cooperative Games:[3] In this type of game, players form alliances or coalitions, and the solution concepts generally involve solving optimization problems across different groups of players. This often requires evaluating multiple possible coalition structures, which can significantly increase computational effort.
- Non-Cooperative Games:[4] Here, each player independently optimizes their strategy without prior agreements with others. The best possible strategy is determined by iteratively solving and comparing different choices while taking into account the responses of other players.
- Stackelberg Games:[5] These hierarchical games involve a leader-follower dynamic, where one player makes a move first, and the others respond accordingly. Solving such games requires a combination of backward and forward

[2] M Imran Azim et al. "Peer-to-peer kilowatt and negawatt trading: A review of challenges and recent advances in distribution networks". In: *Renewable and Sustainable Energy Reviews* 169 (2022), p. 112908.

[3] John Nash. "Two-person cooperative games". In: *Econometrica: Journal of the Econometric Society* (1953), pp. 128–140.

[4] Takako Fujiwara-Greve. *Non-cooperative game theory*. Springer, 2015.

[5] Pu-yan Nie and Pei-ai Zhang. "A note on Stackelberg games". In: *2008 Chinese Control and Decision Conference*. IEEE. 2008, pp. 1201–1203.

motion, often leading to high computational complexity due to the need for extensive tree-based exploration.

- Mixed Strategy Games:[6] In these games, players do not rely on fixed choices but instead use probability distributions over multiple strategies. Finding equilibrium solutions involves solving nonlinear optimization problems, which can be computationally demanding, especially as the number of possible strategies increases.

These explanations have been added to the thesis in chapter 2 in section 2.6 and 2.7, respectively.

> **2**: What are the limitations of the Hong's 2m Point Estimation Method in the context of this work?

Response: The candidate expresses her gratitude to the examiner for asking this question. Hong's 2m Point Estimation Method generates 2m points corresponding to m uncertain variables. Compared to other uncertainty-handling techniques, the number of required iterations increases to only $2m$ times, making it computationally more efficient than many alternative methods. This efficiency is one of the key reasons for selecting this method in this thesis.

However, like other statistical approaches, Hong's 2m method has certain limitations such as the following.

- Assumption of Specific Probability Distributions: The accuracy of this method depends on the assumption that uncertainties follow a predefined probability distribution. In practical scenarios, especially in complex systems, uncertainties may not always align with standard distributions, leading to estimation errors.

- Fixed Sampling Approach: The method relies on a predetermined set of points for numerical integration, which may not be flexible enough to adapt to dynamically changing uncertainties in real-time applications.

Despite these limitations, Hong's 2m Point Estimation Method remains a useful tool due to its balance between computational efficiency and accuracy, making it a preferred choice for uncertainty quantification in many practical applications.

> **3**: The Candidate is advised to include more details on how dynamic network usage charges are calculated and their impact on energy transactions.

Response: The candidate expresses her gratitude for the examiner's comment. The network utilization charges ($\Lambda_{n,m,t}^{NUC}$) when n^{th} community buys power $P_{n,m,t}^{c2c}$

[6] Ido Erev and Alvin E Roth. "Predicting how people play games: Reinforcement learning in experimental games with unique, mixed strategy equilibria". In: *American economic review* (1998), pp. 848–881.

from m^{th} community at t^{th} time are calculated using locational marginal prices (LMP) of the bus containing community n and m in the following way.

$$\Lambda^{NUC}_{n,m,t} = \begin{cases} \frac{1}{2} max(\lambda^{LMP}_{t,n} - \lambda^{LMP}_{t,m}) & \text{if } P^{c2c}_{n,m,t} \geq 0 \text{ and } (\lambda^{LMP}_{t,n} - \lambda^{LMP}_{t,m}) \geq 0\,, \\ 0 & \text{if } P^{c2c}_{n,m,t} \geq 0 \text{ and } (\lambda^{LMP}_{t,n} - \lambda^{LMP}_{t,m}) < 0\,, \\ \frac{1}{2} max(\lambda^{LMP}_{t,m} - \lambda^{LMP}_{t,n}) & \text{if } P^{c2c}_{n,m,t} < 0 \text{ and } (\lambda^{LMP}_{t,m} - \lambda^{LMP}_{t,n}) \geq 0\,, \\ 0 & \text{if } P^{c2c}_{n,m,t} < 0 \text{ and } (\lambda^{LMP}_{t,m} - \lambda^{LMP}_{t,n}) < 0\,. \end{cases}$$

According to the above equation, the Network Utilization Charge (NUC) is applied when power is exported from a higher LMP bus to a lower LMP bus. The LMPs are determined using Optimal Power Flow (OPF), which considers voltage levels, line limits, and other relevant factors. If a peer-to-peer (P2P) energy exchange violates any system constraints, this is reflected in the LMP, leading to an increase in the NUC. The higher NUC then discourages excessive power exchange, prompting communities to adjust their exchanged power values. These updated values are subsequently used in the next OPF calculation. This iterative process continues until the difference between successive LMP values falls within an acceptable tolerance. In this way, the NUC helps manage line loading and voltage limits effectively.

The above description has been added to the thesis in chapters 5,6 and 7 on pages 98, 124, and 168, respectively.

4: How does the proposed framework handle voltage and line loading violations in real-time scenarios?

Response: The candidate expresses her gratitude to the examiner for this question. The proposed framework addresses voltage and line loading violations caused by peer-to-peer (P2P) energy exchange in the day-ahead scheduling phase through the Network Utilization Charge (NUC), as discussed earlier. In real-time scenarios, the P2P exchanged power remains fixed at its day-ahead scheduled value, and real-time scheduling is then carried out. If any violations occur in real-time due to unforeseen fluctuations, the Distribution System Operator (DSO) manages them using its own resources. The additional cost incurred by the DSO for handling these violations is then fairly allocated to the communities based on the deviation in their net injection from day-ahead scheduling to real-time operation. This ensures system stability while maintaining fairness in cost distribution.

5: The Candidate is advised to comment on the key challenges in implementing the proposed frameworks in real-world scenarios.

Response: The candidate is grateful to the examiner for this insightful question. Implementing the proposed framework in real-world scenarios presents several key challenges such as the following.

- Data Availability and Accuracy – The effectiveness of the framework depends on the availability and accuracy of real-time and day-ahead data, including load forecasts, generation schedules, and network conditions. Any inaccuracies can impact the efficiency of peer-to-peer (P2P) trading and network utilization charges (NUC).
- Communication and Coordination – Reliable communication among prosumers, communities, and the Distribution System Operator (DSO) is essential. However, ensuring seamless data exchange in real-time while maintaining cybersecurity and privacy remains a significant challenge.
- Regulatory and Market Constraints – The integration of P2P energy trading into existing regulatory frameworks may require policy modifications. Establishing standardized rules for NUC implementation and cost allocation is necessary to facilitate fair participation.
- Computational Complexity – The iterative process of adjusting NUC, re-evaluating Optimal Power Flow (OPF), and conducting real-time scheduling requires significant computational resources. Large-scale implementation may necessitate advanced optimization techniques and high-performance computing. To reduce this complexity to some extent, the concept of virtual communities has been used in this work. However, in real-world scenarios, these virtual communities should be aggregation of buildings having different load patterns to achieve the goal of reducing the grid dependency. This is, again, a challenge in implementation in a given demographic location.
- Consumer Participation and Acceptance – Encouraging active community participation in P2P trading requires awareness, trust, and suitable incentives. Resistance to new pricing mechanisms and uncertainty regarding economic benefits could hinder adoption.

The candidate acknowledges that overcoming these challenges requires technological advancements, regulatory support, and strong collaboration among stakeholders to ensure the successful deployment of the proposed framework. This response has been incorporated in the thesis in chapter 8 in section 8.2.

Suggestions for modification

Chapter 1:

1: Background and Motivation:

> **a**: Provide more specific examples of recent advancements in P2P energy trading to set the context effectively.

Response: The candidate is grateful to the examiner for the follow-up question. To provide more specific examples, recent advancements in peer-to-peer

(P2P) energy trading have been driven by the integration of innovative technologies and the growing interest in decentralized energy markets. Some notable examples are as follows.

- Power Ledger (India)[7] – The Uttar Pradesh government partnered with Powerledger and ISGF to pilot blockchain-based peer-to-peer (P2P) energy trading for rooftop solar power. This initiative, the first of its kind in India, demonstrated the feasibility of trading solar energy among households, lowering the market buy price by 43%. The successful project led to a regulatory framework that supports broader P2P trading, enhancing affordable energy distribution, especially in rural areas. In 2022, the project won a World Summit Award for its contribution to sustainability.
- Power Ledger (Australia)[8] – Power Ledger is one of the pioneering platforms in the P2P energy trading space. Using blockchain technology, it enables individuals to buy and sell excess solar energy directly with each other. In 2020, Power Ledger expanded its use to multiple projects worldwide, including a partnership with Singapore Power to test P2P trading among local solar producers. This platform ensures secure, transparent, and efficient transactions, allowing for decentralized energy trading while avoiding the need for central utilities.
- Brooklyn Microgrid (USA)[9] – Located in New York, the Brooklyn Microgrid is a community-driven P2P energy trading project where residents can buy and sell solar power using blockchain technology. The project uses smart meters to track energy consumption and production, allowing participants to trade energy directly, without relying on the centralized grid. The Brooklyn Microgrid has become a prominent example of how P2P trading can enhance energy independence and reduce reliance on large utility companies.
- SonnenCommunity (Germany)[10] – Sonnen, a German company, operates the SonnenCommunity, a platform that enables participants to trade surplus solar energy with one another. The company uses its home battery storage systems, combined with a smart grid, to facilitate local energy exchanges. This decentralized trading model has expanded to several countries, including the USA and Australia, and continues to demonstrate the potential for community-driven energy markets that leverage renewable energy and battery storage solutions.

These advancements exemplify how P2P energy trading is rapidly evolving with the help of blockchain, smart grids, and renewable energy integration. These

[7] Powerledger. *Uttar Pradesh Government, India*. Accessed: 2025-02-05. 2025. URL: `https://powerledger.io/clients/uttar-pradesh-government-india/`.

[8] Power Ledger. *Power Ledger*. [Online]. Available: https://www.powerledger.io/. 2021. URL: `https://www.powerledger.io/`.

[9] Brooklyn Energy. *Brooklyn Energy*. [Online]. Available: https://www.brooklyn.energy/. 2025. URL: `https://www.brooklyn.energy/`.

[10] Sonnen Group. *Vision*. [Online]. Available: https://sonnengroup.com/vision/. 2025. URL: `https://sonnengroup.com/vision/`.

projects not only contribute to more sustainable and efficient energy systems but also promote energy independence and local community empowerment. These advancements have been incorporated in the thesis in chapter 2 in section 2.4.

b: Clarify the transition from traditional electricity systems to decentralized models with quantitative data or case studies.

Response: The candidate is grateful to the examiner for this insightful question. The transition from traditional electricity systems to decentralized models is driven by the increasing penetration of renewable energy sources, advancements in digital technologies, and the need for more flexible and resilient energy systems. This shift is characterized by a move away from large, centralized power plants toward locally distributed generation, energy storage, and peer-to-peer (P2P) energy trading.

Traditional electricity systems rely on large-scale generation from fossil fuel or nuclear power plants, with electricity transmitted over long distances to consumers via a centralized grid. In contrast, decentralized models integrate localized generation, such as solar photovoltaics (PV) and wind turbines, enabling consumers (prosumers) to generate, store, and trade electricity within their communities. This transition reduces transmission losses, enhances grid reliability, and supports sustainable energy consumption. The followings are some of the case studies and quantitative data.

- Germany's Energiewende (Energy Transition):[11] Germany's Energiewende policy is a leading example of large-scale decentralization. In 2020, renewable energy accounted for 50.5% of Germany's electricity generation, up from just 6% in 2000. Over 1.6 million small-scale renewable energy producers, including households and businesses, now contribute to decentralized electricity generation. The government has encouraged decentralized generation through feed-in tariffs (FiTs) and community energy cooperatives, where local communities collectively invest in and manage renewable energy projects. These efforts have led to a substantial reduction in carbon emissions and have demonstrated how decentralized models empower local energy consumers.

- Brooklyn Microgrid (USA):[12] The Brooklyn Microgrid in New York is an example of a blockchain-based decentralized energy trading system. It allows residents with solar panels to sell excess energy directly to their neighbors through a peer-to-peer (P2P) marketplace. power outages. Smart contracts ensure transparent and secure energy transactions. This initiative highlights

[11] Fraunhofer ISE. *Public Electricity Generation 2023: Renewable Energies Cover the Majority of German Electricity Consumption for the First Time.* [Online]. Available: https://www.ise.fraunhofer.de/en/press-media/press-releases/2024/public-electricity-generation-2023-renewable-energies-cover-the-majority-of-german-electricity-consumption-for-the-first-time.html. 2024. URL: https://www.ise.fraunhofer.de/en/press-media/press-releases/2024/public-electricity-generation-2023-renewable-energies-cover-the-majority-of-german-electricity-consumption-for-the-first-time.html.

[12] Energy, *Brooklyn Energy*.

how digitalization, combined with decentralized energy generation, can create a self-sufficient local energy market.

- India's Decentralized Solar Expansion : India has witnessed rapid growth in decentralized energy models. Accordinf to[13] Over 10 GW of rooftop solar capacity has been installed as of 2023, contributing to local energy self-sufficiency. The Delhi P2P solar trading pilot project[14] allows consumers to trade solar power using blockchain technology, ensuring secure and efficient transactions. Decentralized solar mini-grids in rural areas have improved energy access for millions of people who were previously off-grid. India's approach demonstrates how decentralized energy models can enhance energy security, promote renewables, and support economic development.

The transition from traditional electricity systems to decentralized models is well underway, supported by technological advancements, policy incentives, and growing consumer participation. Case studies from Germany, the USA, and India, along with global trends, highlight how decentralized energy solutions improve grid resilience, empower local communities, and accelerate the shift toward a more sustainable energy future. This description has been incorporated in the thesis in chapter 1 in section 1.1.

2: Literature Survey:

a: Include a visual summary (e.g., a table or diagram) comparing key studies and their contributions to highlight research gaps more clearly.

Response: The candidate thanks the examiner for this suggestion. A table (Table 1.1 in the thesis) has already been added in the thesis for comparing key studies and their contributions to highlight research gaps more clearly.

b Provide a stronger justification for the selected game-theoretic approaches by contrasting them alternative methods.

Response: The candidate wants to sincerely thanks the examiner for this question. In this thesis, both cooperative and non-cooperative game has been used in this work. The rationale for choosing particular models is based on several key factors:

- Market Structure and Participant Behavior: The choice between cooperative and non-cooperative game models depends on the market structure and the level of collaboration among participants.

[13] Bridge to India. *India Solar Rooftop Map - December 2023*. [Online]. Available: `https://bridgetoindia.com/report/india-solar-rooftop-map-december-2023/`. 2023. URL: `https://bridgetoindia.com/report/india-solar-rooftop-map-december-2023/`.

[14] Tata Power-DDL. *Distributed Energy Resources (DER) Initiative with ISGF and Power Ledger*. [Online]. Available: `https://www.tatapower-ddl.com/corporate/smart-grid-index/DER`. 2025. URL: `https://www.tatapower-ddl.com/corporate/smart-grid-index/DER`.

- Non-Cooperative Models: These are typically chosen when participants act independently and compete with each other.
- Cooperative Models: These are selected when participants can form coalitions or have incentives to collaborate.

- Information Availability: The selection of game models also depends on the level of information available to participants.
  - Complete Information Games: When all participants have full knowledge of others' strategies and payoffs, models like the subgame perfect equilibrium can be used.
  - Incomplete Information Games: In scenarios where participants have limited information about others, Bayesian game models are more appropriate. This is common in energy markets where participants may not know others' cost structures or generation capacities.

- Complexity and Computational Feasibility: The choice of game model also depends on the computational resources available and the complexity of the problem.
  - Simplified Models: For large-scale systems or when quick decisions are needed, simplified game models like potential games or aggregative games might be preferred.
  - Complex Models: When detailed analysis is required and computational resources are available, more complex models like stochastic games or multi-level games can be employed.

By carefully analyzing these factors, the candidate formulated the model based on different scenarios, utilizing cooperative and non-cooperative game theories in different chapters, respectively. This description has been incorporated in the thesis in chapter 2 in section 2.7.

3: Research Gap:

a: Expand the discussion on the limitations of existing methods for handling network constraints and privacy concerns.

Response: The candidate thanks the examiner for suggesting an expanded discussion on existing method limitations. The candidate plans to add a dedicated subsection that critically analyzes the shortcomings of current approaches for handling network constraints and privacy concerns in P2P energy trading. This will emphasize how the proposed work advances the state-of-the-art in addressing these crucial challenges. Modification:

Based on a comprehensive literature review, several critical research gaps have been identified in the field of peer-to-peer (P2P) energy trading systems. This section outlines these gaps and their implications for future research directions.

- Scalability and Privacy Trade-offs: A significant challenge in existing P2P energy trading approaches is the trade-off between scalability and privacy preservation. As the number of participants in the system increases, the computational complexity grows substantially,[15] leading to increased communication burden. This scalability issue often compromises the privacy of participants, highlighting the need for more efficient algorithms that can maintain privacy while handling large-scale systems.

- Geographical Considerations in Energy Sharing: Current P2P energy sharing models[16] often assume geographical proximity of participating buildings. However, this assumption may not hold in all scenarios. For geographically distant buildings, loss coefficients must be incorporated into the models to account for transmission losses. Future research should focus on developing more comprehensive models that can accurately represent energy sharing across varied geographical distances.

- Network Constraints and Technical Feasibility: The existing literature[17] has not extensively explored the impact of network constraints on P2P energy transactions, potentially leading to technically infeasible solutions. Current approaches to address this issue include:

  - Pre-fixed network usage charges,[18] which provide inadequate control over energy transactions with respect to network constraints.
  - Explicit inclusion of constraints in problem formulations,[19] which may lead to security issues due to the need for DSOs to share sensitive data with participants.
  - Involvement of third-party agents[20] , potentially compromising privacy.

  Future research should focus on developing methods that effectively incorporate network constraints while maintaining security and privacy.

[15] Liyang Han, Thomas Morstyn, and Malcolm McCulloch. "Incentivizing prosumer coalitions with energy management using cooperative game theory". In: *IEEE Transactions on Power Systems* 34.1 (2018), pp. 303–313.

[16] Hailing Zhu, Khmaies Ouahada, and Adnan M Abu-Mahfouz. "Peer-to-peer energy trading in smart energy communities: A lyapunov-based energy control and trading system". In: *IEEE access* 10 (2022), pp. 42916–42932; Saqib Iqbal et al. "A novel approach for system loss minimization in a peer-to-peer energy sharing community DC microgrid". In: *International Journal of Electrical Power & Energy Systems* 129 (2021), p. 106775; Amrit Paudel et al. "Peer-to-peer energy trading in a prosumer-based community microgrid: A game-theoretic model". In: *IEEE Transactions on Industrial electronics* 66.8 (2018), pp. 6087–6097.

[17] Xuan He et al. "A New Cooperation Framework With a Fair Clearing Scheme for Energy Storage Sharing". In: *IEEE Transactions on Industrial Informatics* 18.9 (2021), pp. 5893–5904; Amir Anees, Tharam Dillon, and Yi-Ping Phoebe Chen. "A novel decision strategy for a bilateral energy contract". In: *Applied Energy* 253 (2019), p. 113571.

[18] Thomas Baroche et al. "Exogenous cost allocation in peer-to-peer electricity markets". In: *IEEE Transactions on Power Systems* 34.4 (2019), pp. 2553–2564; Amrit Paudel et al. "Peer-to-peer energy trading in smart grid considering power losses and network fees". In: *IEEE Transactions on Smart Grid* 11.6 (2020), pp. 4727–4737.

[19] Weifeng Zhong et al. "Cooperative P2P energy trading in active distribution networks: An MILP-based Nash bargaining solution". In: *IEEE Transactions on Smart Grid* 12.2 (2020), pp. 1264–1276.

[20] Mohsen Khorasany, Yateendra Mishra, and Gerard Ledwich. "Hybrid trading scheme for peer-to-peer energy trading in transactive energy markets". In: *IET Generation, Transmission & Distribution* 14.2 (2020), pp. 245–253.

- Dynamic Role Assignment: Many existing works[21] pre-classify participants into buyers and sellers. However, a more flexible approach is needed, allowing participants to autonomously switch roles based on market scenarios and other participants' strategies. This dynamic role assignment would better reflect real-world conditions and improve overall system efficiency.
- Fair Pricing Mechanisms To encourage consumer participation in local energy trading, there is a need for suitable pricing mechanisms that distribute benefits fairly among participants without violating their privacy. Developing such mechanisms requires a delicate balance between economic incentives and privacy preservation.
- Renewable Energy Uncertainty The intermittent nature of renewable energy generation poses a significant challenge to P2P energy-sharing frameworks. Future research should focus on developing robust models that can effectively handle uncertainties related to renewable energy generation, ensuring system stability and reliability.
- Integration of Dispatchable Distributed Generation The simultaneous consideration of P2P trading and active participation of dispatchable Distributed Generation (DG) units has not been adequately addressed in existing literature. Further investigation is needed to understand the effects of active DG participation on P2P trading frameworks under various scenarios. This research could lead to more beneficial solutions that leverage the flexibility of dispatchable DG units within P2P energy trading systems.

In conclusion, addressing these research gaps will be crucial for the development of more robust, efficient, and widely applicable P2P energy trading systems. Future research efforts should focus on tackling these challenges to unlock the full potential of P2P energy trading in the evolving energy landscape. This description has been incorporated in the thesis in chapter 1 in section 1.3.

b: Emphasize the novelty of the proposed work in addressing these gaps

Response: The candidate sincerely thanks the examiner for the valuable feedback. The candidate understands that it is important to emphasize the novelty of the proposed work in the addressed gap in the mentioned in the previous comments. Thus, based on the modified research gap, the objectives of the thesis is also modified as given below.

[21] Fangyuan Si et al. "Cost-efficient multi-energy management with flexible complementarity strategy for energy internet". In: *Applied Energy* 231 (2018), pp. 803–815; Anees, Dillon, and Chen, "A novel decision strategy for a bilateral energy contract"; Paudel et al., "Peer-to-peer energy trading in a prosumer-based community microgrid: A game-theoretic model"; Mohsen Khorasany, Yateendra Mishra, and Gerard Ledwich. "A decentralized bilateral energy trading system for peer-to-peer electricity markets". In: *IEEE Transactions on industrial Electronics* 67.6 (2019), pp. 4646–4657; Yanni Jiang et al. "Electricity trading pricing among prosumers with game theory-based model in energy blockchain environment". In: *Applied Energy* 271 (2020), p. 115239.

- To design a decentralized P2P energy-sharing framework that integrates BESS and addresses uncertainties in renewable generation, ensuring the preservation of network constraints and enabling secure energy exchange among buildings. The framework also incorporates the concept of virtual communities (VCs), where buildings on the same bus are grouped to reduce the computational burden and communication complexity in large systems.
- To develop a game-theoretic-based algorithm for optimizing energy trading mechanisms (including B2B, B2C, and P2P transactions) within virtual communities. The algorithm aims to ensure fair pricing, privacy preservation, and efficient handling of network constraints. The concept of virtual communities is key here, as it helps aggregate energy exchanges within a bus, reducing the number of participants and simplifying transactions while maintaining the integrity of network operations.
- To implement a practical real-time and day-ahead energy trading system that incorporates dynamic pricing mechanisms, network usage charges, and cloud-based communication, facilitating secure data sharing with the Distribution System Operator (DSO) for effective coordination. The virtual communities concept is integral to this implementation, ensuring that energy exchanges are managed efficiently across multiple geographical locations while addressing privacy and scalability concerns.

These three objectives encapsulate the core design, development, and implementation aspects of the thesis, aligning with the broader research goal of creating an efficient and practical P2P energy trading framework. This description has been incorporated in the thesis in chapter 1 in section 1.4.

Chapter 2:

1: Game Theory Concepts:

> **a**: Include examples to illustrate the differences between cooperative and non-cooperative games in the context of energy trading.

Response: The candidate wants to express her gratitude towards the examiner for this suggestion. Cooperative and non-cooperative games represent two distinct approaches to modeling interactions in energy trading scenarios. To illustrate the differences between these game types, a simple energy trading between various buildings equipped with flexible load, renewable generation resource. The access generated energy can be sold to the peer buildings or can to the grid back. The game can be formulated for this scenario with buildings as participants. The objective is to minimize the total energy consumption cost by changing is strategy which is the power exchanged with the grid and other buildings, and the load shifting. A cooperative and non-coopertive game can be formulated and the key difference between them will be the following.

- Objective: Cooperative games aim to maximize collective benefits, while non-cooperative games focus on individual profit maximization.

- Information Sharing: In cooperative games, participants may share information to optimize joint strategies. Non-cooperative games typically involve limited information exchange.
- Benefit Distribution: Cooperative games require mechanisms to fairly distribute collective gains, whereas in non-cooperative games, each participant's payoff is directly determined by market outcomes.
- Strategy Formation: Cooperative games involve joint strategy formulation, while non-cooperative games feature independent decision-making.
- Market Impact: Cooperative games can lead to more stable market outcomes and potentially higher overall efficiency, whereas non-cooperative games may result in more dynamic and competitive market conditions.

By understanding these differences, energy market participants and regulators can better design and participate in various trading mechanisms, balancing the benefits of cooperation with the dynamics of competition in the evolving energy landscape. This description has been incorporated in the thesis in chapter 2 in section 2.6.3.

b: Clarify the rationale for selecting specific game-theoretic models.

Response: The candidate expresses her gratitude for the examiner's suggestion. The selection of specific game-theoretic models in energy trading scenarios is crucial for accurately representing and analyzing complex interactions between market participants. The rationale for choosing particular models is based on several key factors:

- Market Structure and Participant Behavior: The choice between cooperative and non-cooperative game models depends on the market structure and the level of collaboration among participants.
  - Non-Cooperative Models: These are typically chosen when participants act independently and compete with each other.
  - Cooperative Models: These are selected when participants can form coalitions or have incentives to collaborate.
- Information Availability: The selection of game models also depends on the level of information available to participants.
  - Complete Information Games: When all participants have full knowledge of others' strategies and payoffs, models like the subgame perfect equilibrium can be used.
  - Incomplete Information Games: In scenarios where participants have limited information about others, Bayesian game models are more appropriate. This is common in energy markets where participants may not know others' cost structures or generation capacities.

- Complexity and Computational Feasibility: The choice of game model also depends on the computational resources available and the complexity of the problem.
  - Simplified Models: For large-scale systems or when quick decisions are needed, simplified game models like potential games or aggregative games might be preferred.
  - Complex Models: When detailed analysis is required and computational resources are available, more complex models like stochastic games or multi-level games can be employed.

By carefully considering these factors, researchers and practitioners can select the most appropriate game-theoretic models to accurately represent and analyze energy trading scenarios, leading to more insightful results and effective market designs. This description has been incorporated in the thesis in chapter 2 in section 2.7.

2: Alternating Direction Method of Multipliers:

a: Provide a detailed explanation of the algorithm with a flowchart for better comprehension.

Response: The candidate is thankful for the recommendation to provide more details on ADMM. The ADMM algorithm is used to solve the distributed optimization problem in P2P energy trading. It allows for the decomposition of the global optimization problem into smaller subproblems that can be solved locally by each participant. The flowchart of ADMM algorithm is shown in Figure1. The basic idea behind ADMM is to divide the original problem into a series of smaller subproblems that can be solved separately. These subproblems are then solved iteratively, with each iteration consisting of three main steps:

1. **Splitting**: The original problem is split into smaller subproblems that can be solved independently. This splitting is usually based on the structure of the objective function and the constraints.
2. **Solving**: Each subproblem is solved individually, typically using well-established optimization techniques. These subproblems can often be solved more efficiently and accurately than the original problem.
3. **Updating**: After solving the subproblems, the solutions are combined or updated to obtain an improved solution for the original problem. This step involves updating certain Lagrange multipliers or dual variables to enforce the consistency between the subproblem solutions.

Consider the following optimization problem:

$$minimize\ f(x) + g(z) \tag{1}$$

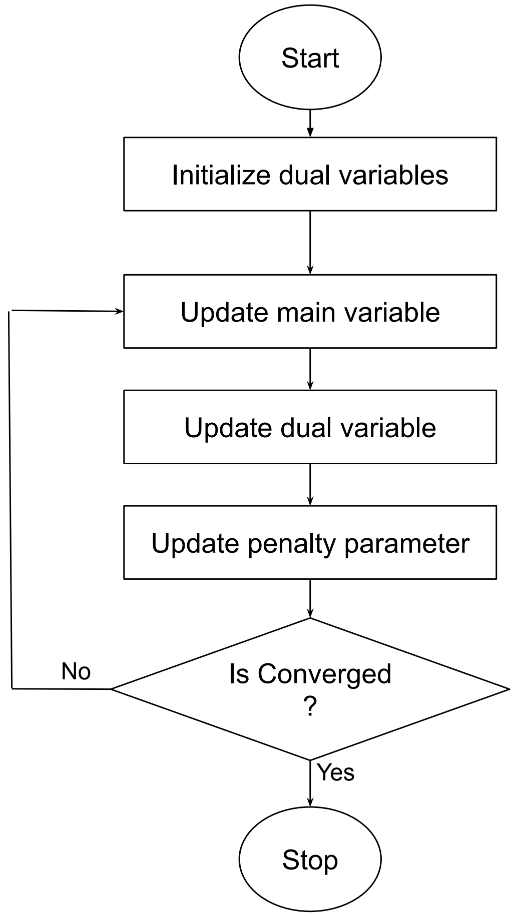

Figure 1: Flowchart of ADMM Algorithm

subject to

$$Ax + Bz = c \tag{2}$$

Where,

- x is the optimization variable of size n,
- z is the optimization variable of size m,
- A is a constraint matrix of size $p \times n$,
- B is a constraint matrix of size $p \times m$,
- c is a vector of size p,
- $f(x)$ is a convex function that depends only on x,
- $g(z)$ is a convex function that depends only on z.

The augmented Lagrangian is formed as,

$$L(x, z, y) = f(x) + g(z) + (y^T)(Ax + Bz - c) + (\rho/2)||Ax + Bz - c||^2 \quad (3)$$

where y is the dual variable, and ρ is the penalty factor. Combining the linear and quadratic terms and scaling the dual variable makes the ADMM more convenient. This scaled form of ADMM is given by

$$L(x, z, a) = f(x) + g(z) + (\rho/2)||Ax + Bz - c + a||^2 - (\rho/2)||a||^2 \quad (4)$$

where $a = (1/\rho)y$ and is called as the scaled dual variable.

The ADMM algorithm for solving this optimization problem can be described as follows.

Step 1: Initialization

Initialize the optimization variables: x^0, z^0, and a^0 (Lagrange multiplier or dual variable) to some initial values.

Step 2: Iteration

- For k = 0, 1, 2, ...
- Update x^{k+1}:

$$x^{k+1} = argmin\ \{f(x) + (\rho/2)\|Ax + Bz^k - c + a^k\|^2\} \quad (5)$$

- Update z^{k+1}:

$$z^{k+1} = argmin\ \{g(z) + (\rho/2)\|Ax^{k+1} + Bz - c + a^k\|^2\} \quad (6)$$

- Update a^{k+1}:

$$a^{k+1} = a^k + (Ax^{k+1} + Bz^{k+1} - c) \quad (7)$$

Step 3: Convergence check

Repeat Step 2 until convergence is achieved, typically by monitoring the change in the objective function or the optimization variables.

The primal and dual feasibility provide sufficient and necessary optimal conditions. At iteration $k + 1$ the primal residual r^{k+1} and dual residual s^{k+1} is given by

$$r^{k+1} = Ax^{k+1} + Bz^{k+1} - c \quad (8)$$

$$s^{k+1} = \rho A^T B(z^{k+1} - z^k) \quad (9)$$

As the ADMM proceeds, both residuals r^{k+1} and s^{k+1} converge to zero.

In ADMM, ρ is a parameter that controls the trade-off between the objective function and the constraint violation. Choosing an appropriate value for ρ is important for achieving good convergence properties. In the literature, many variations of this algorithm have been explored. One such variation includes the use of different penalty parameters for each iteration, as given below:

$$\rho^{k+1} := \begin{cases} \rho^k/\nu, & \text{if } \alpha r^k < s^k \\ \mu\rho^k & \text{if } r^k > s^k\alpha, \\ \rho^k & \text{otherwise .} \end{cases} \tag{10}$$

where ν, μ, and α are parameters.

The main idea behind ADMM is the alternating updates of the optimization variables x and z, while keeping the Lagrange multipliers fixed. The Lagrange multiplier acts as a coordination variable that enforces the consistency between the solutions of the subproblems. By iteratively updating x, z, and a, ADMM aims to find a solution that satisfies both the objective function and the constraints of the original problem. This description has been incorporated in the thesis in chapter 2 in section 2.7.

b: Discuss the computational challenges associated with ADMM and how they are mitigated.

Response: The candidate expresses her gratitude for this question to the examiner. The Alternating Direction Method of Multipliers (ADMM) algorithm, while powerful for distributed optimization in peer-to-peer (P2P) energy trading, presents several computational challenges. This thesis addresses these challenges and implements mitigation strategies to enhance the algorithm's efficiency and applicability. The key computational challenges and their mitigations are as follows:

- Convergence Speed: ADMM may require many iterations to converge, especially for complex problems. To address this, this thesis employs careful tuning of the penalty parameter ρ, which plays a crucial role in the algorithm's convergence rate. The tuning is done based on primal and dual residuals.

- Communication Overhead: ADMM requires frequent information exchange between participants, which can lead to significant communication overhead. The thesis mitigates this by reducing the number of transactions by aggregating the buildings into virtual communities. Minimizing the amount of information shared between participants, focusing only on essential variables like energy exchange values and prices1.

- Computational Complexity: ADMM can be computationally intensive, especially for large-scale systems with many participants. This thesis mitigates this challenge by reducing the number of transactions by aggregating the buildings into virtual communities.

- Risk of communication failure: ADMM requires frequent information exchange regarding update of main and dual variables. Any failure can halt the system process. In this thesis, to mitigate this issue, it is assumed that the communication infrastructure is robust.

By addressing these computational challenges, the thesis presents an ADMM-based P2P energy trading system that is more efficient, scalable, and practical for real-world applications. This description has been added in the thesis in chapter 2 in section 2.7.

Chapter 3:

1: Methodology:

- Add a step-by-step description of the Nash Bargaining and ADMM process to improve clarity.

Response: The candidate wants to thanks the examiner for this question as this will enhance the quality of this thesis. Using Generalised Nash Bargaining (GNB), the problem in Chapter 3 can be formulated as,

$$\max_{\mathbb{E}(P)} \prod_{b=1}^{n} (\mathbb{E}(C_b^{w/o\ b2b}) - \mathbb{E}(C_b^{with\ b2b})), \tag{11}$$

subjected to the associated constraints. This maximization function aims to maximize the collective difference in cost between scenarios without P2P energy trading and with P2P energy trading for all participants. The product of these individual differences is used to emphasize that, in cooperative games, participants collaborate to maximize mutual benefits.This problem can be rewritten as the following.

$$\min_{\mathbb{E}(P)} \sum_{b=1}^{n} -log(\mathbb{E}(C_b^{w/o\ b2b}) - \mathbb{E}(C_b^{with\ b2b}) + 1), \tag{12}$$

The above problem is solved in a decentralized way using ADMM. The coupling constraints can be dealt with the help of new auxiliary variables $\sigma^{\pi}_{i,j}$, $\sigma^{\rho}_{i,j,t}$ and $\sigma^{P}_{i,j,t}$ such that,

$$\sigma^{\pi}_{i,j} = \pi_{i,j}, \tag{13}$$

$$\sigma^{\pi}_{i,j} + \sigma^{\pi}_{j,i} = 0, \tag{14}$$

$$\sigma^{\rho}_{i,j,t} = \rho^{b2b}_{i,j,t}, \tag{15}$$

$$\sigma^{\rho}_{i,j,t} - \sigma^{\rho}_{j,i,t} = 0, \tag{16}$$

$$\sigma^{P}_{i,j,t} = \mathbb{E}(P^{b2b}_{i,j,t}), \tag{17}$$

$$\sigma^{P}_{i,j,t} + \sigma^{P}_{j,i,t} = 0. \tag{18}$$

The expression (12) can be re-written in the augmented Lagrangian form as,

$$\mathcal{L}(\mathbb{E}(P), \sigma, \omega) = \sum_{b=1}^{n} -log\Big(\mathbb{E}(C_b^{w/o\ b2b}) - \mathbb{E}(C_b^{with\ b2b}) + 1\Big)$$
$$+ \frac{\delta_1}{2} \sum_{b=1}^{n} \sum_{\substack{b'=1 \\ b' \neq b}}^{n} (\pi_{i,j} - \sigma^{\pi}_{i,j} + \frac{\omega^{\pi}_{i,j}}{\delta_1})^2 + \frac{\delta_2}{2} \sum_{t=1}^{T} \sum_{b=1}^{n} \sum_{\substack{b'=1 \\ b' \neq b}}^{n} (\mathbb{E}(P^{b2b}_{i,j,t}) - \sigma^{P}_{i,j,t} + \frac{\omega^{P}_{i,j,t}}{\delta_2})^2, \tag{19}$$

where δ_1 and δ_2 are penalty parameters, and $\omega^{\pi}_{i,j}$ and $\omega^{P}_{i,j,t}$ are dual multipliers.

An algorithm for this two-step optimization is given in Algorithm 1 for solving the incentive-based energy-sharing optimization problem. In the first step, the strategies will be optimized wherein $\{P^b_{i,t}, P^s_{i,t}, P^{ls}_{i,t}, P^{ch}_t P^{dis}_t, \pi_{i,j}, P^{b2b}_{i,j,t}\}$ are decided/optimized by using 19. Then in step 2 the auxiliary variables are updated by the minimizing the following lagrangian function.

$$\mathcal{L}(\sigma,\omega) = \frac{\delta_1}{2}\sum_{b=1}^{n}\sum_{\substack{b'=1\\b'\neq b}}^{n}(\pi_{i,j}-\sigma^{\pi}_{i,j}+\frac{\omega^{\pi}_{i,j}}{\delta_1})^2+\frac{\delta_2}{2}\sum_{t=1}^{T}\sum_{b=1}^{n}\sum_{\substack{b'=1\\b'\neq b}}^{n}(\mathbb{E}(P^{b2b}_{i,j,t})-\sigma^{P}_{i,j,t}+\frac{\omega^{P}_{i,j,t}}{\delta_2})^2, \tag{20}$$

Once all the variables (strategies and auxiliary) are obtained, the dual multipliers are updated as shown in steps 8 and 9. Finally, the penalty parameters, δ_1 and δ_2, are updated with the help of primal and dual residuals. Here, τ and ν are given parameters. This algorithm is for incentive-based energy sharing model. For an hourly price-based energy sharing, the same algorithm will be used by replacing $\pi_{i,j}$ with $\rho^{b2b}_{i,j,t}$ and modifying it accordingly. (19) will also be modified with the help of (15) and (16).

	Algorithm 1	
1	Initialize tolerance, $\delta(1), \tau, \nu, \omega(1) = 0, \kappa = 1$	
2	Do	
3	For each player	
4	$\min_{\mathbb{E}(P)\in\gamma} \mathcal{L}(\mathbb{E}(P), \sigma(\kappa), \omega(\kappa))$	{First Step}
5	Update $\sigma(\kappa+1)$:	
6	$\min_{\sigma\in(14,18)} \mathcal{L}(\mathbb{E}(P(\kappa+1)), \sigma, \omega(\kappa))$	{Second Step}
7	Update $\omega(\kappa+1)$:	
8	$\omega^{\pi}(\kappa+1) = \omega^{\pi}(\kappa) + \delta_1(\kappa)(\pi_{i,j}(\kappa+1) - \sigma^{\pi}_{i,j}(\kappa+1))$	
9	$\omega^{P}(\kappa+1) = \omega^{P}(\kappa) + \delta_2(\kappa)(\mathbb{E}(P^{b2b}_{i,j,t}(\kappa+1)) - \sigma^{P}_{i,j,t}(\kappa+1))$	
10	Calculate primal and dual residuals	
11	$\lambda^P_1 = \|\|\pi_{i,j}(\kappa+1) - \sigma^{\pi}_{i,j}(\kappa+1)\|\|$	
12	$\lambda^P_2 = \|\|\mathbb{E}(P^{b2b}_{i,j,t}(\kappa+1)) - \sigma^{P}_{i,j,t}(\kappa+1)\|\|$	
13	$\lambda^D_1 = \|\|\sigma^{\pi}_{i,j}(\kappa+1) - \sigma^{\pi}_{i,j}(\kappa)\|\|$	
14	$\lambda^D_2 = \|\|\sigma^{P}_{i,j,t}(\kappa+1) - \sigma^{P}_{i,j,t}(\kappa)\|\|$	
15	If $\lambda^P > \frac{1}{\tau}\lambda^D$, then	
16	$\delta(\kappa+1) = \nu\delta(\kappa)$	
17	else if $\lambda^P < \tau\lambda^D$, then	
18	$\delta(\kappa+1) = \frac{1}{\nu}\delta(\kappa)$	
19	else	
20	$\delta(\kappa+1) = \delta(\kappa)$	
21	end if	
22	$\kappa = \kappa + 1$	
23	while $\|\|\omega(\kappa+1) - \omega(\kappa)\|\| >$ *tolerance*	

This description has been added to the thesis in chapter 3 in section 3.3.1.

2: Simulation Results:

- Include sensitivity analysis to assess the robustness of the stochastic model.

Response: The candidate is grateful to the examiner for suggesting the inclusion of sensitivity analysis to assess the robustness of the stochastic model. This addition will significantly enhance the quality of the thesis. A comprehensive sensitivity analysis is conducted on the proposed stochastic model by varying the mean values of the uncertainty data. Specifically, five scenarios will be examined: Base case (0% change in mean), 5% decrease in mean, 10% decrease in mean, 5% increase in mean, and 10% increase in mean, respectively. For each scenario, the total cost is calculated both with and without B2B energy trading through pricing mechanism. The results are presented in Table 1, demonstrating the model's performance across different uncertainty levels.
Preliminary results indicate that B2B energy trading consistently reduces total costs across all scenarios, suggesting the robustness of the proposed model. This analysis provides valuable insights into the model's behavior under varying levels of uncertainty and strengthen the validity of the conclusions drawn from the stochastic framework.

Table 1: Sensitivity analysis of the proposed stochastic model

		Build1	Build2	Build3	CBESS	Total	Percentage Decrease
Case 1 (μ)	**Cost without B2B**	167.1236	36.96736	84.37675	1.328233	289.7959	25.86984878
	Cost with B2B (Price)	148.382	18.22421	65.63521	-17.4152	214.8262	
Case 2 (0.95μ)	**Cost without B2B**	187.4214	50.57768	91.51644	1.328233	330.8438	20.08964978
	Cost with B2B (Price)	170.8057	33.95916	74.90055	-15.287	264.3784	
Case3 (0.9μ)	**Cost without B2B**	208.3448	65.0854	99.24413	1.328233	374.0026	15.80007766
	Cost with B2B (Price)	193.5704	50.31416	84.47101	-13.4457	314.9099	
Case 4 (1.05μ)	**Cost without B2B**	148.0539	24.64487	77.44371	1.328233	251.4707	32.09458114
	Cost with B2B (Price)	127.8694	4.468996	57.26757	-18.8437	170.7622	
Case 5 (1.1μ)	**Cost without B2B**	130.1332	13.91172	70.71208	1.328233	216.0852	38.37478325
	Cost with B2B (Price)	109.3971	-6.81583	49.98016	-19.3985	133.163	

This description has been added in the thesis in chapter 3 in section 3.4.

Chapter 4:

1: Methodology:

- Explain the role of virtual communities in reducing computational complexity with quantitative comparisons.

Response: The candidate is thankful to the examiner for raising this important query regarding the role of virtual communities (VCs) in reducing computational complexity. Virtual communities group buildings into aggregated entities, effectively reducing the number of decision-making participants in P2P energy trading. This aggregation simplifies optimization by:

- Reducing transaction variables: Instead of individual buildings negotiating with all others, VCs act as intermediaries, lowering the number of bilateral interactions.

- Hierarchical decomposition: Complex large-scale problems are split into smaller sub-problems (intra-VC and inter-VC optimization).

In the context of this thesis, the advantages of this aggregation of buildings into virtual communities with quantitative comparisons are as follows.

- Transaction Volume Reduction: For 30 buildings grouped into 3 VCs
  - Without VCs: $30 \times 29 = 870$ potential B2B transactions.
  - With VCs: $3 \times 2 = 6$ C2C transactions + 10 intra-VC transactions per VC = 36 total transactions (approx 95% reduction).
- Parallelization: If there are n buildings total and m VCs, then there are approximately $\frac{n}{m}$ buildings in each VC. With parallelization, all three VCs can perform their intra-VC optimization at the same time. In the ideal case, the time required to solve the intra-VC optimization for all three VCs is approximately the same as the time required to solve the intra-VC optimization for one VC. If the sequential processing time is $3\times$ f($\frac{n}{m}$) and the parallel processing time is f($\frac{n}{m}$), then the parallel computation is approximately $\frac{1}{3}$ the time of the sequential processing. The reduction in computation is $\frac{(3-1)}{3} = \frac{2}{3}$, or about 66%. Thus, the parallelization reduces sequential computations by 66%. It is a very rough estimate based on the idea that the computation of all intra-VC optimizations can happen in parallel, significantly reducing the overall runtime.
- Data Aggregation: VCs share only net energy profiles with the DSO, avoiding individual building-level data exchange.

These results validate that virtual communities critically enhance scalability while preserving solution quality, making large-scale P2P energy trading computationally feasible.

2: Simulation Results:

- Provide a comparative analysis of the proposed model with other scalable frameworks.

Response: The candidate wants to sincerely thanks the reviewer for this question. The proposed framework focuses on the aggregation of buildings into virtual communities. Table 2 compares the total cost of buildings in the P2P energy trading framework with and without virtual communities. While the variation in individual building costs is minimal, the difference in total execution time is significant, as shown in the table. The proposed framework reduced execution time by 48 minutes compared to the existing literature. Thus, it can be concluded that aggregating buildings into virtual communities reduces computational complexity and execution time for P2P energy trading.

Table 2: Comparison Table

Proposed Framework			Other Framework	
C1	B1	86.6766	B1	88.1155
	B2	78.6481	B2	76.0011
	B3	86.2124	B3	85.0169
C2	B1	72.3017	B4	91.9939
	B2	-7.5833	B5	6.6372
	B3	-35.0367	B6	-19.7233
C3	B1	36.1164	B7	39.1162
	B2	178.4923	B8	166.8947
	B3	119.3154	B9	111.5659
	Sum	615.1428	Sum	645.6179
	Total Execution Time	1:31:18.826	Total Execution Time	2:19:02.387

This description has been added to the thesis in chapter 4 in section 4.4.

Chapter 5:

1: Problem Formulation:

a: Clearly define the assumptions and limitations of the proposed model.

Response: The candidate thanks the examiner for this comment as it enhances the quality of the thesis. For the game-theoretic model presented in the thesis, following assumptions[22] were made.

- Agreement: In cooperative game theory, it is assumed that players engage in discussions or negotiations before the game begins, leading to a formal agreement among all participants. This assumption ensures that players can coordinate their strategies to achieve mutually beneficial outcomes. Conversely, in non-cooperative games, it is assumed that no binding agreements are made before the game starts, and each player acts independently to maximize their own payoff.
- Reliable Communication Infrastructure: The models in this study assume that the communication channels used by players are robust, free from disruptions, and do not introduce delays. This ensures that information exchange between players occurs seamlessly, which is crucial in strategic decision-making processes.

[22] Borm, *On game theoretic models and solution concepts.*

- Rational Player Behavior: It is assumed that all players behave rationally, meaning they make decisions that maximize their expected utility based on the available information. The possibility of irrational behavior, such as decision-making influenced by emotions or biases, is not considered in this study..
- Multiple Strategies for Each Player: Each player in the game is assumed to have access to multiple strategic choices. This ensures that the game captures a wide range of possible interactions and outcomes rather than being restricted to a limited set of actions.
- Common Knowledge: All players are aware of the game's rules, possible strategies, and payoffs, and they also know that all other players have this knowledge.
- Static Virtual Community Formation: The virtual community structure remains fixed during the optimization period, without considering dynamic adjustments based on changing conditions.

These assumptions may also be considered as the limitation of the proposed model. Apart from these limitations, the proposed model has the following limitations.

- Limited Consideration of Uncertainty: While the model incorporates renewable energy generation, it may not fully capture the complex uncertainties associated with load forecasting, equipment failures, and market dynamics.
- Lack of Dynamic Community Formation: The assumption of static virtual communities may limit the model's ability to adapt to changing conditions and exploit potential benefits from dynamic community restructuring.
- Potential for Strategic Behavior: The model does not explicitly address the potential for participants to engage in strategic behavior, such as gaming the pricing mechanism or manipulating data to gain unfair advantages.

These assumptions and limitations should be considered when interpreting the results and applying the model to real-world scenarios. Future research efforts can focus on addressing these limitations and enhancing the model's robustness and applicability. This description has been added to the thesis in chapter 2 in section 2.6.

b: Justify the choice of Nash Bargaining for handling the network constraints.

Response: The candidate expresses her gratitude towards the examiner. The Nash bargaining model has not been used here for handling the network constraints. It is used for P2P energy trading at different levels in the proposed model.

2: Simulation Results:

a Present a detailed analysis of the impact of network constraints on energy trading outcomes.

Response: The candidate wants to thank the examiner for this question. In this thesis, energy trading among the participants is indirectly influenced by the network constraints through network utilization charges (NUC). For studying its impact, a separate case is considered in Chapter 4 and Chapter 7, where the NUC is not considered.

In chapter 4 *Case III* corresponds to the case where B2B, B2C and C2C transactions are considered and in *Case IV*, in addition to *Case III*, penalty charges based on the distance between VCs are also considered in C2C transactions. Table 3 shows the total power imported and exported separately in C2C trading in *Case III* and *Case IV*. Due to the penalty imposed in *Case IV*, the imported/exported power decreases compared to *Case III*

Table 3: Community-to-community power exchange

		C1	**C2**	**C3**
$P_{im}^{C2C}(kW)$	$CaseIII$	316.2523	176.2641	482.0041
	$CaseIV$	221.878	105.9789	267.3148
$P_{ex}^{C2C}(kW)$	$CaseIII$	197.3159	607.631	169.5414
	$CaseIV$	71.04568	436.5601	87.52149

In chapter 7, the *Case III* corresponds to the case where B2B, B2C and C2C transactions are considered with network constraints and $Case\ III^*$ is similar to *Case III* except network constraints are ignored. Table 4 shows the cost of all the buildings in different virtual communities with and without considering network constraints, respectively. As can be seen from this table, the consideration of network constraints increases the LMPs and eventually the NUCs reducing the energy exchange. Thus, the cost in *Case III* is comparatively higher compared to $Case\ III^*$.

Table 4: Cost ($) comparison in terms of network constraints

	VC1				**VC2**				**VC3**			
	B_1	B_2	B_3	**Sum**	B_1	B_2	B_3	**Sum**	B_1	B_2	B_3	**Sum**
Case III	94.187	84.505	91.534	270.226	75.311	-6.923	-34.477	33.911	54.257	231.105	150.046	435.408
$Case\ III^*$	93.60	83.77	91.24	268.61	73.55	-5.864	-37.26	30.43	46.04	193.43	131.07	370.55

b Highlight the advantages of the dynamic network usage charges with numerical evidence.

Response: The candidate expresses her gratitude for the examiner's comment. The network utilization charges ($\Lambda_{n,m,t}^{NUC}$) when n^{th} community buy $P_{n,m,t}^{c2c}$ from m^{th} community at t^{th} time is calculated using locational marginal prices (LMP) of the bus containing community n and m in the following way.

$$\Lambda_{n,m,t}^{NUC} = \begin{cases} \frac{1}{2} max(\lambda_{t,n}^{LMP} - \lambda_{t,m}^{LMP}) & \text{if } P_{n,m,t}^{c2c} \geq 0 \text{ and } (\lambda_{t,n}^{LMP} - \lambda_{t,m}^{LMP}) \geq 0\,, \\ 0 & \text{if } P_{n,m,t}^{c2c} \geq 0 \text{ and } (\lambda_{t,n}^{LMP} - \lambda_{t,m}^{LMP}) < 0\,, \\ \frac{1}{2} max(\lambda_{t,m}^{LMP} - \lambda_{t,n}^{LMP}) & \text{if } P_{n,m,t}^{c2c} < 0 \text{ and } (\lambda_{t,m}^{LMP} - \lambda_{t,n}^{LMP}) \geq 0\,, \\ 0 & \text{if } P_{n,m,t}^{c2c} < 0 \text{ and } (\lambda_{t,m}^{LMP} - \lambda_{t,n}^{LMP}) < 0\,. \end{cases}$$

According to the above equation, the Network Utilization Charge (NUC) is applied when power is exported from a higher LMP bus to a lower LMP bus. The LMPs are determined using Optimal Power Flow (OPF), which considers voltage levels, line limits, and other relevant factors. If a peer-to-peer (P2P) energy exchange violates any system constraints, this is reflected in the LMP, leading to an increase in the NUC. The higher NUC then discourages excessive power exchange, prompting communities to adjust their exchanged power values. These updated values are subsequently used in the next OPF calculation. This iterative process continues until the difference between successive LMP values falls within an acceptable tolerance. In this way, the NUC helps manage line loading and voltage limits effectively.

To show the numerical evidence, Figure 2 (Figure 5.9(b) in the thesis) is used in this thesis that compares the LMPs of three VC and the base grid price. The $VC3$ is located at 18^{th} bus, which is also known to be the leaf bus for the IEEE 33 bus system. Due to its location, the voltage will be most critical at this bus, and thus, the highest LMP is expected. This can be seen from Figure 2, where the LMP of $VC3$ is higher compared to the other VCs.

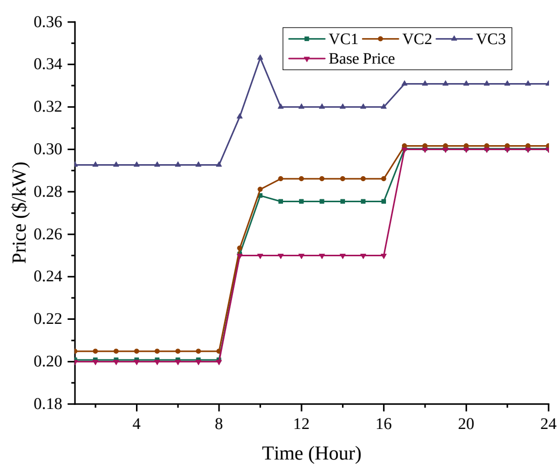

Figure 2: LMPs of three VCs and the base price

By dynamically increasing the network charges during periods of high congestion, NUCs incentivize prosumers to reduce their energy exports/imports, thereby alleviating congestion and improving network stability. NUCs encourage prosumers to adjust their reactive power output to support voltage levels, leading to a more balanced and stable voltage profile across the distribution network.

Chapter 6:

1: Methodology:

- Provide more detail on the modified KS bargaining solution and its advantages over traditional methods.

Response: The candidate expresses his gratitude to the examiner. The modified Nash bargaining solution or Kalai-Smorodinsky (KS) bargaining solution is an approach to resolving bargaining problems that offers several advantages over traditional methods like the Nash bargaining solution. It aims to find a fair compromise between players by maintaining the ratio of their maximal gains. It uses the "utopia point" or "aspiration point" (best possible outcome for each player) and "disagreement point" (worst acceptable outcome) as reference points.

In the KS bargaining solution, the ratio of distances from the disagreement point, d_i (a point where all players receive their reservation payoffs, i.e., the payoff they would receive if they did not reach an agreement) to the optimal point, c_i^* and the aspiration point, a_i (the point where all players receive the highest payoff they can imagine getting in the negotiation) is the same for all players. Now, the KS bargaining solution is a compromise between the two extreme points of disagreement and aspiration. Specifically, it is the point on the line connecting the two extreme points that is equidistant from them. In other words, it is the point that minimizes the sum of the distances to the disagreement point and the aspiration point.

If we consider two players in this negotiation, let's assume that they have different disagreement and aspiration points. Then, the KS bargaining solution is the point that satisfies the condition: $d_1^x + d_2^x = a_1^x + a_2^x$. Here d_1^x and d_2^x are the distances from the KS point to the disagreement points of players 1 and 2, respectively, and a_1^x and a_2^x are the distances from the KS point to the aspiration points of players 1 and 2, respectively.

Now, suppose that we change the disagreement and aspiration points of Player 1, but keep the ones of Player 2 the same. Then, the KS bargaining solution will change, but it will still satisfy the above condition. This is because the distances d_2^x and a_2^x remain the same, while the distances d_1^x and a_1^x change, but in such a way that their sum remains constant. Therefore, the ratio of d_1^x to a_1^x remains the same, and this ratio is the same for both players, meaning that the ratio of distances from the disagreement point of the optimal and aspiration point is the same for all the players. Therefore, for n player game, the KS bargaining solution, c_i^*, is given by

$$\underset{c}{max} \prod_{i}^{i \in n} (d_i - c_i) \tag{21}$$

subjected to

$$\frac{d_1 - c_1}{d_1 - a_1} = \frac{d_2 - c_2}{d_2 - a_2} = ... = \frac{d_n - c_n}{d_n - a_n} \tag{22}$$

The advantages of this method over traditional methods are given below.

- The KS solution ensures that players' relative gains are proportional to their maximum potential gains, leading to a more equitable outcome.
- Unlike the Nash solution, which satisfies independence of irrelevant alternatives, the KS solution considers the entire set of alternatives when determining the outcome.
- The KS solution often provides a more balanced compromise between competing objectives, especially in cases where one player has significantly more bargaining power.

By addressing these aspects, the KS bargaining method offers a more better approach for negotiations compared to traditional bargaining solutions. This description has been added in chapter 2 to the thesis in section 2.6.1.2.

2: Simulation Results:

- Include a discussion on potential challenges in implementing DG participation.

Response: The candidate acknowledges the examiner's request to discuss potential challenges in implementing Distributed Generation (DG) participation. Based on the thesis and the provided search results, the following challenges can be identified.

- Technical Integration:
  - Maintaining voltage levels within regulated limits becomes more complex with bidirectional power flow from DGs.
  - Coordinating protection systems and devices to handle reverse power flows.
  - Managing additional cycling and wear on voltage control equipment, especially in rural areas with longer distribution feeders.
- Planning and Operational Challenges:
  - Traditional distribution planning procedures are not adequately designed to account for DG systems.
  - Balancing the goals of increasing DG deployment while minimizing adverse impacts on the distribution system.
  - Incorporating DG into system-wide and distribution-level planning processes.

- Regulatory and Policy Issues:
  - Updating interconnection standards and grid codes to clearly define requirements for DGs.
  - Developing fair and transparent processes for DG interconnection, moving away from 'first-come, first-served' approaches.
- Economic and Market Challenges:
  - Designing appropriate pricing mechanisms and contractual relationships for DG transactions with the grid.
  - Balancing the interests of DG owners, traditional utilities, and non-DG customers.
  - Addressing the potential for cost shifting to non-DG customers.
- Protection and Reliability Concerns:
  - Conventional protection schemes based on overcurrent detection may be insufficient for DG-connected networks.
  - Ensuring selectivity, reliability, and sensitivity of protection schemes in bidirectional power flow scenarios.
  - Developing new protection strategies for active distribution networks and microgrids.
- Communication and Control:
  - Implementing advanced communication systems for coordinating DG operations with the broader grid.
  - Developing control strategies for integrating DG into smart grid operations.
- Market Design and Business Models:
  - Adapting utility business models to accommodate increased DG penetration.
  - Developing new market structures that fairly value DG contributions to the grid.

By addressing these challenges, the integration of DG can be more effectively implemented, leading to a more resilient, efficient, and sustainable power system. This description has been added in chapter 6 to the thesis in section 6.4.

Chapter 7:

1: Energy trading with consideration of distribution Network Constraints:

- Clarify the integration of day-ahead and real-time scheduling with practical examples.

Response: The candidate sincerely thanks the examiner for their insightful query regarding the integration of day-ahead and real-time scheduling, as well as the request for practical examples. In the proposed framework, day-ahead scheduling forms the baseline for real-time operations. The day-ahead schedule is determined based on forecasted data for renewable generation, load demand, and market prices. These schedules optimize energy transactions, including

- Day-ahead schedules calculate building-to-building (B2B), building-to-community (B2C), and community-to-community (C2C) energy exchanges.
- Charging and discharging schedules are optimized to store surplus renewable energy during off-peak hours and discharge it during peak demand periods.
- Adjusting load profiles in response to forecasted demand patterns.
- The schedule determines the quantity of energy imported from or exported to the utility grid.

In real-time operations, these day-ahead schedules act as baseline references but are adjusted dynamically to account for deviations caused by uncertainties in renewable generation or load demand. The real-time adjustments include

- Modifying charging/discharging schedules based on real-time renewable generation and demand fluctuations.
- Balancing discrepancies between scheduled and actual P2P transactions by importing/exporting energy from/to the grid.

Practical Example: Aggregated Profiles of Virtual Community 1 To illustrate this integration, the aggregated load, renewable generation, BESS charging/discharging, and grid exchange power profiles for Community 1 are analyzed as shown in Figure3. These graphs depict these profiles over a 24-hour period.

Day-Ahead Scheduling: During periods of high renewable generation (e.g., midday)(Figure 3(b)), surplus energy is stored in the BESS (Figure 3(c)) or traded with other communities/buildings via P2P transactions. During peak demand hours (around 1700 hours as shown in (Figure 3(a))), stored energy is discharged from the BESS to meet local demand or traded with other participants. Grid imports and exports are minimized as shown in Figure 3(d).

Real-Time Adjustments: The P2P (B2B and C2C) power exchanges are made fixed to the day-ahead values. If actual renewable generation (Figure 3(b)) exceeds forecasts, additional surplus energy is either stored in the BESS or exported to the grid. In case of lower-than-expected generation, additional energy is imported either from BESS (Figure 3(c)) or from the grid (Figure 3(d)).
The graphs (Figure 3) shows how day-ahead schedules align with forecasted trends while real-time adjustments ensure deviations are managed effectively. This integration ensures that day-ahead schedules provide a baseline while real-time adjustments maintain operational efficiency and reliability of the system. The practical example using virtual community 1's aggregated profiles highlights how this

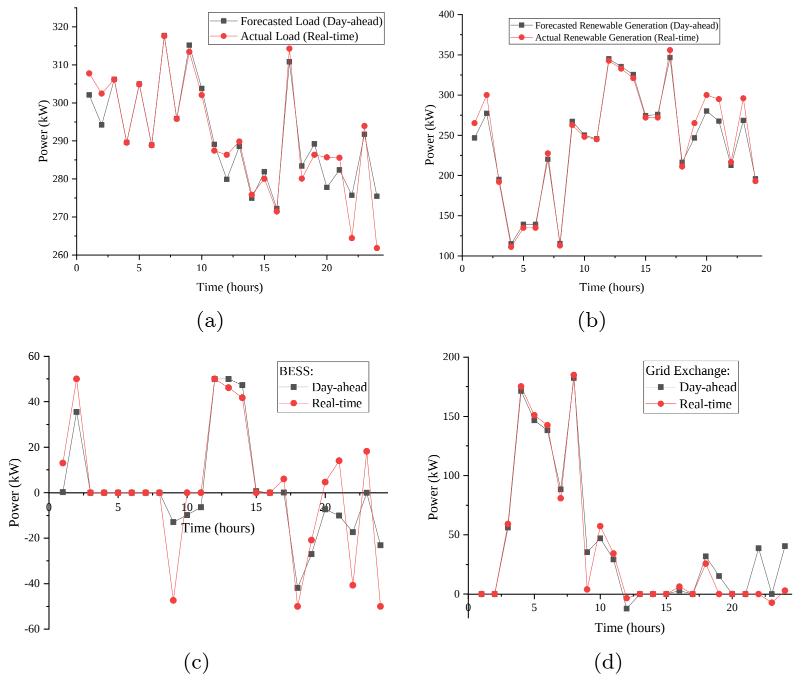

Figure 3: Practical Example: Aggregated Profiles of Virtual Community 1 during day-ahead and real-time operation (a) Load Profile, (b) Renewable generation, (c) BESS charging-discharging power profile, and (d) Grid exchange power profile

dual-stage approach optimizes energy management in a decentralized P2P trading framework. The candidate appreciates this opportunity to elaborate on this critical aspect of the thesis and believes that this explanation clarifies the integration of day-ahead and real-time scheduling effectively. This description has been added in chapter 7 to the thesis in section 7.3.3.

2: Simulation Results:

- Comment on the scalability of the framework with increasing participants.

Response: The candidate wants to sincerely thanks the examiner for this question. This chapter presents a cooperative game based framework for economic benefit through P2P trading among buildings located at same or different bus. The proposed framework addresses the challenges of scalability by introducing the concept of virtual communities (VCs) to group buildings based on their location in the distribution system. This approach reduces the effective number of participants and transactions, thereby enhancing computational efficiency and scalability.

The framework incorporates three levels of energy trading: building-to-building (B2B) within a VC, building-to-community (B2C), and community-to-community

(C2C). The use of a cloud computing platform facilitates P2P transactions without requiring direct data sharing between participants, enhancing privacy and potentially improving scalability. During real-time scheduling, the buildings use day-ahead scheduling data for P2P energy exchange. Thus, in real-time scheduling, the complexity and burden on communication infrastructure reduces making it a more scalable approach.

Virtual communities group buildings into aggregated entities, effectively reducing the number of decision-making participants in P2P energy trading. This aggregation simplifies optimization by:

- Reducing transaction variables: Instead of individual buildings negotiating with all others, VCs act as intermediaries, lowering the number of bilateral interactions.
- Hierarchical decomposition: Complex large-scale problems are split into smaller sub-problems (intra-VC and inter-VC optimization).

In the context of this thesis, the advantages of this aggregation of buildings into virtual communities with quantitative comparisons are as follows.

- Transaction Volume Reduction: For 30 buildings grouped into 3 VCs
  - Without VCs: $30 \times 29 = 870$ potential B2B transactions.
  - With VCs: $3 \times 2 = 6$ C2C transactions + 10 intra-VC transactions per VC = 36 total transactions (approx 95% reduction).
- Parallelization: If there are n buildings total and m VCs, then there are approximately $\frac{n}{m}$ buildings in each VC. With parallelization, all three VCs can perform their intra-VC optimization at the same time. In the ideal case, the time required to solve the intra-VC optimization for all three VCs is approximately the same as the time required to solve the intra-VC optimization for one VC. If the sequential processing time is $3\times$ f($\frac{n}{m}$) and the parallel processing time is f($\frac{n}{m}$), then the parallel computation is approximately $\frac{1}{3}$ the time of the sequential processing. The reduction in computation is $\frac{(3-1)}{3} = \frac{2}{3}$, or about 66%. Thus, the parallelization reduces sequential computations by 66%. It is a very rough estimate based on the idea that the computation of all intra-VC optimizations can happen in parallel, significantly reducing the overall runtime.
- Data Aggregation: VCs share only net energy profiles with the DSO, avoiding individual building-level data exchange.

These results validate that virtual communities critically enhance scalability while preserving solution quality, making large-scale P2P energy trading computationally feasible. Overall, this thesis presents a more scalable approach to P2P energy trading that can accommodate a larger number of participants across diverse locations while maintaining computational efficiency and participant privacy. This description has been added in chapter 7 to the thesis in section 7.3.3.

Examiner 2

The thesis describes the work carried out by the scholar Ms. Monika Misra on the topic of "Game Theoretic Approach to Peer-to Peer Energy Transactions in Active Distribution Networks". The work mainly deals with different models of Peer to Peer (**P2P**) Energy Trading (**ET**) **P2P-ET** with Distributed Generation (DG). The 'Peer to Peer Energy Trading", (**P2P-ET**) is carried out for Modified IEEE 33 bus system. Different types of Energy Trading and Energy Sharing like **Peer to Peer (P2P): Building to Building (B2B); Building to Community (B2C); Community to Community (C2C)** are discussed in this work.
The research work in the thesis is organized into **EIGHT** chapters as shown below.

1. *The introduction is presented in **chapter 1.***
2. *An overview of Peer-to-Peer Energy Trading Frameworks and Methodologies is given in **chapter 2.***
3. *Stochastic Peer-to-Peer Energy Trading Model is described in **chapter 3.***
4. *A Scalable Peer-to-Peer Energy Trading Model is given in **chapter 4.***
5. *Network-Constrained P2P Energy Sharing through Virtual Community, Distribution System Operator, with (DSO) is presented in **chapter 5.***
6. *Peer-to-Peer Energy Trading Model with Active Participation of Distributed Generation is presented in **chapter 6.***
7. V*irtual Community based Peer-to-Peer Energy Trading Model including Real Time Scenarios is presented in **chapter 7.***
8. *Conclusions and Future Scope are listed in **chapter 8.***

Response: The candidate is grateful to the examiner for this in-depth review.

Most of the chapters, namely, 4, 5, 6 and 7, appear to be similar in many aspects, dealing with the **P2P, B2B, C2C and B2C** respectively. Different types of Energy Trading and Energy Sharing models, like *Stochastic, Scalable, Network-Constrained, Virtual Communities. Distribution System Operator, (DSO)* were discussed. An IEEE 33 distribution system model is considered at the end to implement the Real Time Scheduling Scenarios.

Response: The candidate wants to thank the examiner for this question and to draw the kind attention of the examiner towards Table 5. This table discusses the different concepts involved in the various chapters of this thesis. They may seem to have similar aspects. However, the modelling and methodology are quite different from each other. This description has been added in chapter 2 to the thesis in section 2.11. **Remarks on Chapter Tiles:**

Table 5: Different Concepts Involved in Various Chapters of this Thesis

Concepts	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Peer-to-Peer Energy Trading	✓	✓	✓	✓	✓
Multi-community	×	✓	✓	✓	✓
Renewable Uncertainty	✓	×	✓	✓	✓
Game involved	Cooperative Game (Nash Bargaining)	Non-Cooperative Game	Cooperative Game (Nash Bargaining)	Cooperative Game (KS Bargaining)	Cooperative Game (KS Bargaining)
Network Contraints	×	×	✓	✓	✓
Active participation of DGs	×	×	×	✓	✓
Analysis of the effect of DGs' participation actively and marginal cost basis on LMPs	×	×	×	✓	×
Cost analysis of effect of network constraints in Day-ahead scheduling	×	×	×	×	✓
Real-time load scheduling	×	×	×	×	✓
Real-time BESS scheduling	×	×	×	×	✓

1: Chapters 3, 4, 6, 7 use the term '**Peer to Peer Energy Trading**', whereas the title of the thesis is '**Peer-to Peer Energy Transactions**', while chapter 5 uses the term, "**Peer to Peer Energy Sharing**". The scholar should explain the significance of all three and justify the need for using '**Peer-to Peer Energy Transactions**', in the title of the thesis.

Response: The candidate wants to thank the examiner for his valuable feedback and wants to acknowledge the inconsistency in terminology across different chapters of the thesis. The terms "Peer-to-Peer Energy Trading," "Peer-to-Peer Energy Sharing," and "Peer-to-Peer Energy Transactions" are closely related but have distinct implications in the context of decentralized energy systems.

- Peer-to-Peer (P2P) Energy Trading refers specifically to the buying and selling of energy between prosumers and consumers within a decentralized energy market. This involves price negotiations, market mechanisms, and economic transactions.
- Peer-to-Peer (P2P) Energy Sharing focuses more on collaborative energy distribution without necessarily involving monetary transactions. It is used in scenarios where surplus energy is shared among peers for mutual benefit rather than sold at market-determined prices.
- Peer-to-Peer (P2P) Energy Transactions is a broader term that encompasses both trading and sharing of energy. It refers to any form of energy exchange that occurs between peers, regardless of whether it is purely commercial (trading) or cooperative (sharing). The term "Transactions" was chosen in the

thesis title to reflect the inclusiveness of both economic and non-economic energy exchanges occurring in a P2P network.

To maintain consistency and clarity, the chapters are renamed as follows.

- Chapter 3: "A Cooperative Game Analysis of Peer-to-Peer Energy Transactions: Foundation of Virtual Community"
- Chapter 4: "A Non-Cooperative Game Analysis of Peer-to-Peer Energy Transactions Involving Multi-Communities"
- Chapter 5: "Network-Constrained Peer-to-Peer Energy Transactions: A Cooperative Game Analysis Framework"
- Chapter 6: "Peer-to-Peer Energy Transactions in Active Distribution Systems: A Kalai-Smorodinsky Bargaining Framework"
- Chapter 7: "Peer-to-Peer Energy Transactions in Real-Time Scenarios Using the Kalai-Smorodinsky Bargaining Model"

2: Chapters 3, 4, 6, 7 discuss different models of **Peer to Peer Energy Trading**", like *i) Stochastic, ii) Scalable, iii) Distributed Generation, iv) Virtual Community*. **Why** is there a need to consider various models of **P2-PET** models? Instead one **single** widely used **P2-PET** model could have been considered and analyzed in detail.

Response: The candidate wants to thank the examiner for his thoughtful comment. The decision to consider multiple models of Peer-to-Peer Energy Trading (P2-PET) in Chapters 3, 4, 6, and 7 was driven by the complexity and diversity of real-world energy systems. Each model addresses specific challenges and scenarios that cannot be comprehensively analyzed using a single approach. The comparison of chapters on the basis of different concepts involved is shown in Table 6. This description has been added in chapter 2 to the thesis in section 2.11.

Table 6: Different Concepts Involved in Various Chapters of this Thesis

Concepts	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Peer-to-Peer Energy Trading	✓	✓	✓	✓	✓
Multi-community	×	✓	✓	✓	✓
Renewable Uncertainty	✓	×	✓	✓	✓
Game involved	Cooperative Game (Nash Bargaining)	Non-Cooperative Game	Cooperative Game (Nash Bargaining)	Cooperative Game (KS Bargaining)	Cooperative Game (KS Bargaining)
Network Contraints	×	×	✓	✓	✓
Active participation of DGs	×	×	×	✓	✓
Analysis of the effect of DGs' participation actively and marginal cost basis on LMPs	×	×	×	✓	×
Cost analysis of effect of network constraints in Day-ahead scheduling	×	×	×	×	✓
Real-time load scheduling	×	×	×	×	✓
Real-time BESS scheduling	×	×	×	×	✓

3: None of the chapters has the term "**Game Theory**".

Response: The candidate acknowledges the issues related to the title as raised by the examiner. Thus, to maintain consistency and clarity, the chapters are renamed as follows.

- Chapter 3: "A Cooperative Game Analysis of Peer-to-Peer Energy Transactions: Foundation of Virtual Community".
- Chapter 4: "A Non-Cooperative Game Analysis of Peer-to-Peer Energy Transactions Involving Multi-Communities".
- Chapter 5: "Network-Constrained Peer-to-Peer Energy Transactions: A Cooperative Game Analysis Framework".
- Chapter 6: "Peer-to-Peer Energy Transactions in Active Distribution Systems: A Kalai-Smorodinsky Bargaining Framework".
- Chapter 7: "Peer-to-Peer Energy Transactions in Real-Time Scenarios Using the Kalai-Smorodinsky Bargaining Model".

4: It is expected to see chapters with the following titles 1. "**Peer to Peer Energy Trading**":,2 **Game Theoretic Approach to'**"

Response: The candidate expresses gratitude to the examiner for this comment as this helps in enhancing the quality of this thesis. The chapters are renamed as follows.

- Chapter 3: "A Cooperative Game Analysis of Peer-to-Peer Energy Transactions: Foundation of Virtual Community".
- Chapter 4: "A Non-Cooperative Game Analysis of Peer-to-Peer Energy Transactions Involving Multi-Communities".
- Chapter 5: "Network-Constrained Peer-to-Peer Energy Transactions: A Cooperative Game Analysis Framework".
- Chapter 6: "Peer-to-Peer Energy Transactions in Active Distribution Systems: A Kalai-Smorodinsky Bargaining Framework".
- Chapter 7: "Peer-to-Peer Energy Transactions in Real-Time Scenarios Using the Kalai-Smorodinsky Bargaining Model".

Strengths and Weakness:

1:Strengths-1: **Good Selection of the Topic** on Peer to Peer Energy Trading in Active Distribution Networks. Mathematical Problem formulation is good.

Response: The candidate thanks the examiner for his positive feedback on this thesis and appreciates his valuable insights.

2:Strengths-2: **VERY Good Publications** in **Four** Reputed Journals (IEEE Access 2023; IEEE **IoT** (2023); Sustainable Energy Grids and Networks (2024); **IEEE IA** (2024)); Conferences (**NPSC**(2022); **ICEPE**(2023))

Response: The candidate thanks the examiner for such an encouraging feedback.

1:Weakness-1: There are **too many chapters**, namely, eight in number. Five (or Six chapters should be more than sufficient), Most of the Chapters 4, 5, 6 and 7 appear to be similar dealing with the same topics throughout **Peer to Peer (P2P); Building to Building (B2B), Building to Community (B2C); Community to Community (C2C);**

Response: The candidate thanks the examiner for his valuable feedback. While the candidate understands the examiner's concern about the number of chapters and the apparent overlap, the candidate would like to clarify that each chapter presents distinct concepts and methodologies that contribute to the overall analysis of Peer to Peer (P2P), Building to Building (B2B), Building to Community (B2C), and Community to Community (C2C) models. Each chapter addresses a unique aspect of the problem, with careful attention to the different contexts and applications as given in Table 7. This description has been added in chapter 2 to the thesis in section 2.11.

Table 7: Different Concepts Involved in Various Chapters of this Thesis

Concepts	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Peer-to-Peer Energy Trading	✓	✓	✓	✓	✓
Multi-community	×	✓	✓	✓	✓
Renewable Uncertainty	✓	×	✓	✓	✓
Game involved	Cooperative Game (Nash Bargaining)	Non-Cooperative Game	Cooperative Game (Nash Bargaining)	Cooperative Game (KS Bargaining)	Cooperative Game (KS Bargaining)
Network Contraints	×	×	✓	✓	✓
Active participation of DGs	×	×	×	✓	✓
Analysis of the effect of DGs' participation actively and marginal cost basis on LMPs	×	×	×	✓	×
Cost analysis of effect of network constraints in Day-ahead scheduling	×	×	×	×	✓
Real-time load scheduling	×	×	×	×	✓
Real-time BESS scheduling	×	×	×	×	✓

2:Weakness-2: Most of the Chapters 3, 4, 6, 7 discuss different models of **Peer to Peer Energy Trading**", like *i) Stochastic, ii) Scalable, iii) Distributed Generation, iv) Virtual Community*. **Why** is there a need to consider various models of **P2-PET** models? Instead **one single** widely used **P2-PET** model could have been considered and analysed in detail.

Response: The candidate wants to thank the examiner for his thoughtful comment. The decision to consider multiple models of Peer-to-Peer Energy Trading (P2-PET) in Chapters 3, 4, 6, and 7 was driven by the complexity and diversity of real-world energy systems. Each model addresses specific challenges and scenarios that cannot be comprehensively analyzed using a single approach. The comparison of chapters on the basis of different concepts involved is shown in Table 8. This description has been added in chapter 2 to the thesis in section 2.11.

Table 8: Different Concepts Involved in Various Chapters of this Thesis

Concepts	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Peer-to-Peer Energy Trading	✓	✓	✓	✓	✓
Multi-community	×	✓	✓	✓	✓
Renewable Uncertainty	✓	×	✓	✓	✓
Game involved	Cooperative Game (Nash Bargaining)	Non-Cooperative Game	Cooperative Game (Nash Bargaining)	Cooperative Game (KS Bargaining)	Cooperative Game (KS Bargaining)
Network Contraints	×	×	✓	✓	✓
Active participation of DGs	×	×	×	✓	✓
Analysis of the effect of DGs' participation actively and marginal cost basis on LMPs	×	×	×	✓	×
Cost analysis of effect of network constraints in Day-ahead scheduling	×	×	×	×	✓
Real-time load scheduling	×	×	×	×	✓
Real-time BESS scheduling	×	×	×	×	✓

3:Weakness-3: **Why** is there a need to consider **Game Theory** in this work. **None** of the chapters use the term 'Game Theory in their title.

Response: The candidate is grateful for the examiner's insightful question. The incorporation of game theory in this work is essential due to the strategic decision-making involved in peer-to-peer (P2P) energy trading within active distribution networks. In a decentralized system, each participant (whether a building, community, or individual) aims to optimize their own energy usage and trading decisions, while also considering the actions of others. Game theory provides a framework to model these interactions, helping to predict the outcomes of these strategic decisions and identify equilibrium solutions that can lead to efficient and fair energy trading. The game-theoretic concepts are applied to better understand the dynamics between participants, ensuring that the overall energy distribution is optimized for all stakeholders. The candidate hopes this clarifies the relevance of game theory in the context of this research.
The candidate acknowledges the issues related to the title as raised by the examiner. Thus, to maintain consistency and clarity, the chapters are renamed as follows.

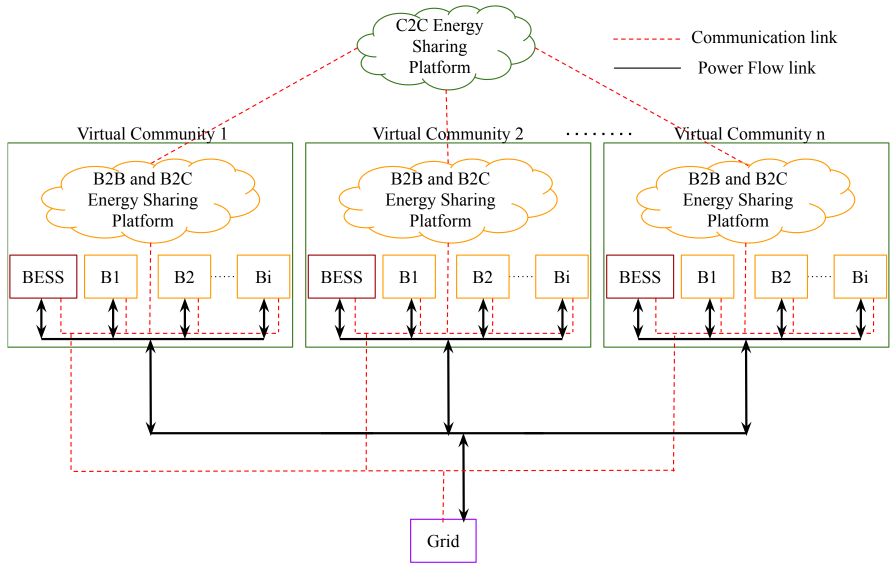

Figure 4: Illustration for P2P Energy Trading

- Chapter 3: "A Cooperative Game Analysis of Peer-to-Peer Energy Transactions: Foundation of Virtual Community".
- Chapter 4: "A Non-Cooperative Game Analysis of Peer-to-Peer Energy Transactions Involving Multi-Communities".
- Chapter 5: "Network-Constrained Peer-to-Peer Energy Transactions: A Cooperative Game Analysis Framework".
- Chapter 6: "Peer-to-Peer Energy Transactions in Active Distribution Systems: A Kalai-Smorodinsky Bargaining Framework".
- Chapter 7: "Peer-to-Peer Energy Transactions in Real-Time Scenarios Using the Kalai-Smorodinsky Bargaining Model".

> **4**:Weakness-4: The illustration of working of the P2P, B2B, C2C, B2C is to be provided.

Response: The candidate is grateful to the examiner for this suggestion. Figure 4 has been added in the manuscript illustrating the working of the P2P energy trading which includes B2B, B2C, and C2C energy trading. This figure has been added in chapter 4 to the thesis as Figure 4.4.

Suggestions for Improvement:

> **SG1**: A New chapter, other than introduction, should be introduced which discusses both the topics of '**Peer to Peer Energy Trading**' and **Game**

theory in **Energy Trading** respectively before the start of chapters 3. Chapter 2 can be renamed and added with more information.

Response: The candidate sincerely thanks the examiner for their valuable suggestion to include a new chapter discussing Peer-to-Peer (P2P) Energy Trading and Game Theory in Energy Trading before the start of Chapter 3. This chapter will provide a comprehensive foundation for understanding these topics and their interrelation, thereby enhancing the coherence and flow of the thesis. Below is the overview of the modified second chapter added in the thesis, titled " Peer-to-Peer Energy Trading Frameworks and Methodologies: An Overview":

Chapter 2: Peer-to-Peer Energy Trading Frameworks and Methodologies: An Overview
2.1 Introduction
2.2 Types of P2P Energy trading models
2.3 Challenges associated with P2P energy trading model
2.4 Recent Advancement in P2P energy trading
2.5 Game Theory Concepts
2.6 Assumption for the Game-theoretic models used
2.7 Choice of Game-theoretic models
2.8 Alternating direction method of multipliers
2.9 Hong's 2m Point Estimation Method (PEM)
2.10 Receding Horizon
2.11 Thesis Layout based on Energy Trading Models
2.12 Summary

SG2: An electrical network analogy of the information in table 4.5 regarding C1, C2, C3: B1, B2, B3 with SPV, WPG, BESS in terms of B2B, P2P, C2C are to be provided.

Response: The candidate is thankful to the examiner for their insightful question. The respective electrical network analogy of the information in table 4.5 regarding C1, C2, C3: B1, B2, B3 with SPV, WPG, BESS in terms of B2B, P2P, C2C is given in Figure 5. This figure has been added to the thesis in chapter 4 as Figure 4.5.

Each building in the B2B energy trading framework can be considered as a node in the equivalent circuit. This is because

- Each building has its own load, renewable energy generation (SPV and WPG), and potentially a battery energy storage system (BESS), making it a distinct entity in terms of power flow.
- The interaction between buildings (energy exchange) can be represented as power flows between nodes in an electrical network.

The buildings are further aggregated into communities, as shown in the figure,

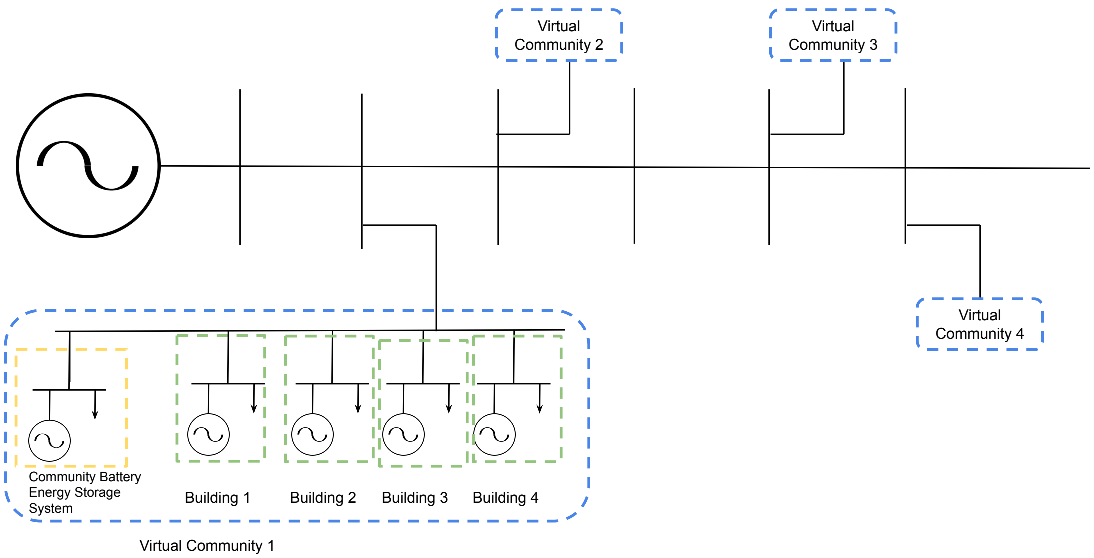

Figure 5: Electrical Network Analogy

resulting in building-to-community(B2C) interactions. The community battery energy storage system (CBESS) acts as an additional node that interacts with all buildings through the community. The buildings interact with buildings of other communities though C2C interactions. Thus, with the help of P2P energy trading at various stages (B2B, B2C, C2C), the cost of all the participants and grid dependency decreases. This equivalent circuit representation effectively models the P2P energy trading framework, with each building considered as a node. This abstraction highlights the interactions among communities, buildings and their shared resources (CBESS), enabling detailed analysis of power flows and cost optimization. The candidate appreciates this opportunity to clarify and enhance the understanding of the proposed framework.

Important Questions:

> **1**: **Q3_1: Why** is there a need to consider **Stochastic Model**? **A Deterministic Model** should be considered and introduced first and discussed in detail.

Response: The candidate agrees with the examiner that a deterministic model should be considered and introduced first in detail. The reasoning behind placing Chapter 3 (the stochastic model with a single community using a cooperative game) before Chapter 4 (the deterministic model with multiple communities using a non-cooperative game) is based on the need to first establish a simpler, more controlled scenario before moving to a more complex and expansive model.

The stochastic model in Chapter 3 introduces key concepts in a single-community setup, allowing for a foundational understanding of energy trading dynamics under uncertainty. By starting with this model, the candidate wanted to set a base for how the cooperative game framework operates in a less complex environment, which can be easily understood before extending these ideas to multiple communities in Chapter 4.

The more complex deterministic model in Chapter 4 then builds upon this foundation by considering a larger-scale, multi-community setup and a non-cooperative game, where participants are independent and seek to optimize their own outcomes. This progression from a simpler to a more complex model aligns with the goal of guiding the reader step-by-step through the concepts.

The candidate hopes this clears up the rationale for the ordering and appreciates the feedback on this matter.

2: **Q3_2:** Is the **B2B Energy Trading** the same as **P2P Energy Trading**?

Response: The candidate sincerely thanks the examiner for the comment and would like to clarify the distinction between B2B (Building-to-Building) Energy Trading and P2P (Peer-to-Peer) Energy Trading. While both B2B and P2P energy trading involve the exchange of energy between entities, they differ in their scope and structure.

P2P energy trading typically refers to the direct energy transactions between independent participants, which can be individuals, buildings, or communities. In this thesis, peers trade energy based on their individual needs and available resources, facilitated through decentralized platforms.

On the other hand, B2B energy trading is more specific to energy exchanges between buildings, which can be part of a larger distribution network. In this case, energy trading occurs within a defined group of buildings, with a focus on optimizing energy consumption and reducing costs within that group.

While both models share similarities in facilitating energy transactions, B2B energy trading can be seen as a subset of P2P energy trading, with a narrower focus on building-to-building interactions rather than broader peer-to-peer exchanges. The candidate hopes this distinction clarifies the differences between B2B and P2P energy trading and appreciates the examiner's inquiry.

3: **Q3_3:** **Where** is the single line diagram (**SLD**) of the **B2B** energy trading diagram?

Response: The candidate sincerely thanks the examiner for this question. The single line diagram (SLD) of the B2B energy trading diagram is shown below (Figure 6). The buildings are grouped into virtual communities as can been from this diagram. This figure has been added in chapter 3 as Figure 3.2.

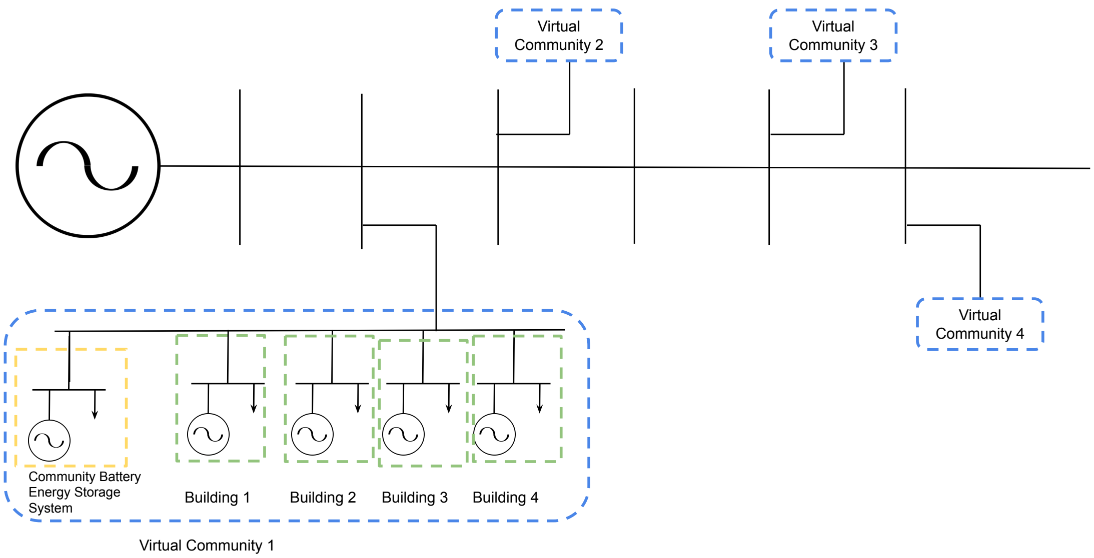

Figure 6: Single line diagram (SLD) for the system

4: **Q3_4:** In Energy trading using B2B, more information on **How** much power and energy sold/purchased OR sell bids and buy bids are to be provided.

Response: The candidate sincerely thanks the examiner for the comment. The information regarding B2B energy sharing is already provided in the thesis within Figure 3.3(A) (in the thesis), which is positive when building buys from others; else it is negative. The respective incentives and hourly prices are shown in Table 3.4 (in the thesis) and Figure 3.3(B) (in the thesis), respectively. The candidate hopes this clarifies the matter and appreciates the examiner's attention to this aspect of the thesis.

5: **Q3_5**: Page 35, the legend for the Algorithm I is missing. This needs to be provided. **What** does this algorithm do? There is no information.

Response: The candidate sincerely thanks the examiner for the comment. Regarding the missing legend for Algorithm 1 on page 35, the candidate acknowledges the oversight and will add a clear description of the algorithm in the legend to ensure that its purpose and functionality are well understood.

To clarify, Algorithm 1 outlines the steps for implementing the P2P energy-trading framework using a cooperative game approach combined with the ADMM (Alternating Direction Method of Multipliers) for optimization. The algorithm facilitates the optimal distribution of energy among participants in the network while considering their individual energy demands and generation capacities. The cooperative game approach ensures that the participants work together to maximize the overall benefit, while the ADMM is used to efficiently solve the optimization problem by decomposing it into smaller subproblems that can be solved iteratively.

The candidate will ensure that this explanation is included in the legend in the thesis for Algorithm 1, to provide a complete understanding of the algorithm's function. This has been modified in the thesis as follows: Algorithm 1: Algorithm for optimizing P2P energy sharing using a cooperative game approach and ADMM to distribute energy efficiently among participants by solving the optimization problem iteratively.

> **6**: **Q3_6:** Table 3.1, **can** each building (build 1, 2, 3) be considered as a node? An equivalent circuit of the same B2B should be provided as a 3 bus/node system. Analysis should be performed. Similar with table 3.3.

Response: The candidate is thankful to the examiner for their insightful question. Yes, each building in the B2B energy trading framework can be considered as a node in the equivalent circuit. This is because

- Each building has its own load, renewable energy generation, and potentially a battery energy storage system (BESS), making it a distinct entity in terms of power flow.
- The interaction between buildings (energy exchange) can be represented as power flows between nodes in an electrical network.
- The community battery energy storage system (CBESS) acts as an additional node that interacts with all buildings.

The equivalent circuit can be drawn as shown in Figure 7. The introduction of B2B energy trading significantly reduces costs for all participants by enabling surplus renewable energy to be shared among buildings. The CBESS further enhances cost savings by storing surplus energy during low-demand periods and discharging it during peak demand. This equivalent circuit representation effectively models the B2B energy trading framework, with each building considered as a node. This abstraction highlights the interactions between buildings and their shared resources (CBESS), enabling detailed analysis of power flows and cost optimization. The candidate appreciates this opportunity to clarify and enhance the understanding of the proposed framework. This figure has been added in chapter 3 as Figure 3.2 and description in section 3.4.

> **7**: **Q3_7:** Fig 3.3 (a), 3.4(a), 3.4(b), **why** is the power from buildings negative? **Are** the buildings prosumers?

Response: The candidate sincerely thanks the examiner for this question. The buildings in the study are indeed prosumers, meaning they can both consume (load) and generate (renewable resources) energy. When buildings generate excess energy, they either sell it back to the grid or share it with other peers.

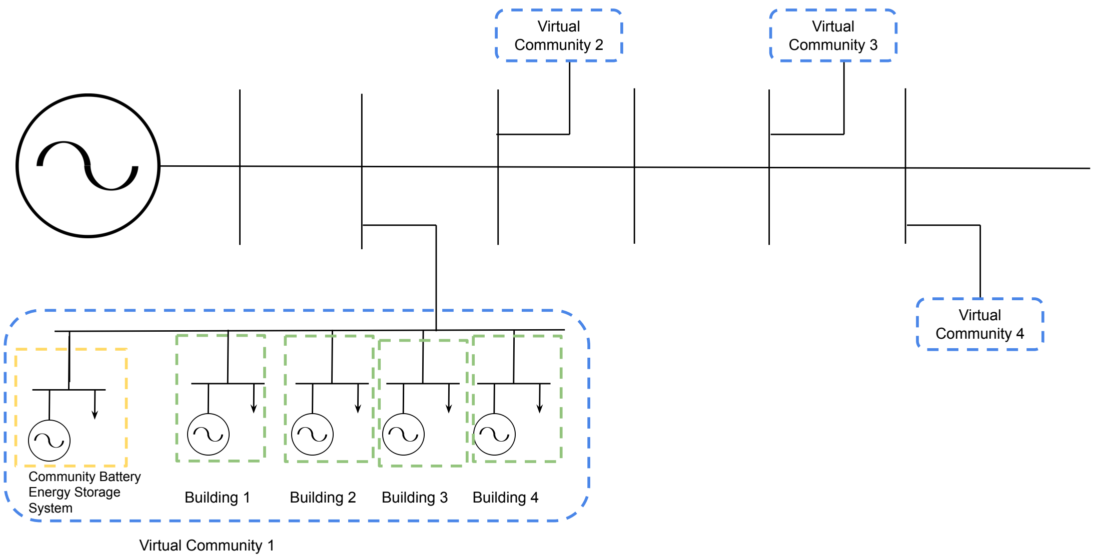

Figure 7: Electrical Network Analogy

The reason the power from buildings appears negative is due to the convention used in the formulation. A negative power value indicates that the building is exporting (selling) energy, while a positive value represents energy consumption. This convention is commonly used in energy trading models to distinguish between energy generation and consumption clearly.

The candidate hopes this clarification addresses the examiner's query.

8: **Q4_1:** Fig 4.1 shows the P2P, B2B and B2C respectively. Is the **Energy Sharing** the same as **Energy Trading**?

Response: The candidate sincerely thanks the examiner for the question. In Fig. 4.1 (in the thesis), the P2P energy sharing framework includes Building-to-Building (B2B), Building-to-Community (B2C), and Community-to-Community (C2C) interactions, all of which fall under the broader concept of P2P energy trading.

Regarding the distinction between energy sharing and energy trading, while both involve the exchange of energy among participants, energy trading typically refers to transactions where energy is bought and sold with associated pricing mechanisms, whereas energy sharing can imply a cooperative exchange without strict financial transactions. However, in the context of this work, the terms are used interchangeably since the framework considers both cooperative and market-based mechanisms for energy exchange. The candidate hopes this explanation clarifies the examiner's query.

> **9**: **Q4_2**: What is the significance of Eqn 4.27? What is being maximized.

Response: The candidate expresses her gratitude to the examiner for such an insightful question. Equation 4.27(in the thesis) is given by the following.

$$\tau(z,q) = \arg max_{q\in(\gamma_b,\gamma_c)}\phi(z,q). \tag{23}$$

Here $\phi(z,q)$ is defined by the following.

$$\phi(z,q) = \sum_{p}^{players} [C_F(z_p, z_{-p}) - C_F(q_p, z_{-p})] - \frac{\delta}{2}||z-q||_2^2. \tag{24}$$

The above function denotes the total gains of player p if it switches from its current strategy z_p to q_p regardless of other players' strategies. Here δ is a known parameter. To find the Genarlised Nash Equilibrium, a regularised Nikaido-Isoda-function (also known as NI-function) is used.[23] In this case, $\phi(z,q)$ is the NI function, where q has the same dimensions as z. The NI function is a fundamental tool for solving generalized Nash equilibrium problems (GNEPs) in game theory. It quantifies the improvement a player could achieve by unilaterally changing its strategy while keeping other players' strategies fixed.

Equation 4.27 (in the thesis) (23) maximizes the deviation potential of each participant in the game by checking whether a better strategy (q) exists compared to the current one (z). At equilibrium, the function value approaches zero, meaning that no participant can improve its objective function unilaterally, indicating that the Generalized Nash Equilibrium (GNE) is reached.

Thus, Equation 4.27 (in the thesis) is crucial for reformulating and solving the GNEP, ensuring the stability and convergence of the non-cooperative game. The candidate hopes this explanation clarifies the examiner's query.

> **10**: **Q4_3: How** and **Why** is Game theory suitable and applicable for P2P/B2B/ B2C Energy Trading/ Energy Sharing. It is not clear Under what circumstances is game theory is found to be suitable?

Response: The candidate expresses her gratitude to the examiner for this insightful question. Game theory is suitable and applicable for C2C, B2B, and B2C energy trading/sharing because these interactions involve multiple decision-making entities (buildings and communities) that strategically optimize their energy exchange based on their individual objectives while considering the actions of others.

The Game Theory is suitable for such interaction due to the following reasons.

- Decentralized Decision-Making: In P2P energy trading, prosumers act independently, making decisions about selling, buying, or sharing energy. Game theory provides a framework to model their strategic interactions.

[23] Francisco Facchinei and Christian Kanzow. "Generalized Nash equilibrium problems". In: *Annals of Operations Research* 175.1 (2010), pp. 177–211.

- Optimization of Benefits: Each participant aims to maximize its own benefit (e.g., minimizing costs or maximizing revenue), and game theory helps determine equilibrium strategies where no participant has an incentive to deviate.

- Fair and Efficient Energy Allocation: Cooperative game theory ensures that participants can form coalitions to share energy in a mutually beneficial way, while non-cooperative game theory helps model competitive scenarios where prosumers act individually.

- Market Stability and Convergence: Game theory ensures that energy transactions reach a stable state (equilibrium), where supply and demand are balanced efficiently

In general, under the following circumstances, Game Theory is found to be suitable.

- Multiple Independent Decision Makers Exist: In P2P/B2B/B2C trading, buildings and communities act as independent decision-makers, making it necessary to model their interactions strategically.

- Strategic Behavior Influences Outcomes: Each participant's decision depends on the decisions of others, making traditional optimization approaches less effective.

- Market-Based and Cooperative Energy Sharing Exists: Both competitive (non-cooperative) and collaborative (cooperative) scenarios can be modeled using game theory.

- Dynamic and Decentralized Systems Are Involved: When energy supply, demand, and pricing are dynamic, game theory provides adaptive and scalable solutions.

In this thesis, game theory is applied to model both cooperative and non-cooperative interactions in various P2P energy-sharing frameworks, ensuring efficient energy distribution and market stability. The candidate hopes this explanation clarifies the examiner's query. This description has been added to the thesis in chapter 2 section 2.6.

> **11**: **Q4_4:** The Algorithm 2 in page 52, should have a legend. What does this algorithm describe?

Response: The candidate sincerely thanks the examiner for the comment. The legend for Algorithm 2 on page 52 will be provided to clearly describe its purpose.

Algorithm 2 presents the P2P energy sharing framework using a non-cooperative game and ADMM (Alternating Direction Method of Multipliers). In this framework, buildings are grouped into virtual communities, and energy trading occurs in B2C, B2B, and C2C settings. The algorithm searches for the optimal energy trading strategy for each participant irrespective of the strategies of others, aligning with the principles of a non-cooperative game. ADMM is used to efficiently solve the decentralized optimization problem by breaking it into smaller subproblems that each participant can solve iteratively while maintaining privacy. This ensures computational efficiency and convergence to an optimal trading strategy.

The candidate will ensure that this explanation is included as the legend for Algorithm 2 in this thesis to improve clarity in the following way.

Algorithm 2: Algorithm for P2P energy sharing using a non-cooperative game and ADMM, where buildings in virtual communities optimize their energy trading strategies independently.

> **12**: **Q4_5:** Sec 4.3.2.1, What is C2C Price? How is it different from B2B and P2P prices?

Response: The candidate sincerely thanks the examiner for the comment. The C2C price refers to the P2P energy exchange price between different virtual communities, whereas B2B prices correspond to P2P energy trading at the building level. The key differences are as follows.

- C2C Price (Community-to-Community Price): This is the price determined for energy trading between different virtual communities. It is calculated first to establish the cost of energy exchange at the community level.
- B2B Price (Building-to-Building Price): This is the energy trading price between individual buildings within the same community. It governs the direct exchange of energy between prosumer buildings.
- P2P Price (Peer-to-Peer Price): This is a general term encompassing all decentralized energy trading interactions, including B2B, B2C, and C2C.

The pricing structure follows a hierarchical approach. C2C Price is calculated first to determine the cost of energy exchange between virtual communities. The total cost of each community is then divided among its buildings using the B2C price (Building-to-Community Price). The B2B price is incorporated along with other cost factors to determine the total cost of each building. This pricing mechanism ensures fair and efficient cost distribution across different levels of energy exchange. The candidate hopes this explanation clarifies the examiner's query. This description has been added to the thesis in chapter 4 section 4.3.2.

> **13**: **Q4_6**: Figs 4.5 to 4.8 results on building to utility power exchange is good. Some values are-ve. **Is** this energy exchange bidirectional? If so, **where** are the **energy prices** and **energy blocks** during exchange?

Response: The candidate is appreciative of the examiner's question. Yes, the energy exchange in Figures. 4.5 to 4.8 is bidirectional, meaning buildings and communities can both buy and sell energy depending on their surplus or deficit.

Negative values indicate energy export (selling), while positive values represent energy import (buying).

The energy prices for different exchanges (Community-to-Utility, Community-to-Community, Building-to-Building, and Building-to-Community) are already determined in the pricing mechanism discussed in the thesis through Figure 4.9 and 4.10 (in the thesis). These include C2C, B2B, and B2C prices, which govern the cost of energy transfer at each level. The energy blocks or the amount of energy traded are defined in the optimization framework and vary dynamically based on the demand and supply conditions of the participants. These values are explicitly provided in the results and figures illustrating the energy flow among entities as can be seen from Figures 4.5 to 4.8 (in the thesis). The candidate hopes this explanation clarifies the examiner's query.

14: **Q5_1:** Figs 5.1 and 4.1 appear to be similar. **Are** chapters 4 and 5 similar also?

Response: The candidate is grateful to the examiner for this question. Yes, Figure 5.1 and 4.1 appears to be similar. However the difference is present due to the presence of the DSO (distribution system operator) in Figure 5.1 as compared to Figure 4.1.

Table 9: The difference in Chapter 4 and Chapter 5

Concepts	**Chapter 4**	**Chapter 5**
Peer-to-Peer Energy Trading	✓	✓
Multi-community	✓	✓
Renewable Uncertainty	×	✓
Game involved	Non-Cooperative Game	Cooperative Game (Nash Bargaining)
Network Contraints	×	✓

As can be seen from Table 9, the chapter 4 and 5 are not similar, as they address different aspects of P2P energy trading with distinct methodologies and considerations.

Chapter 4 focuses on a non-cooperative game-theoretic approach for P2P energy trading without considering network constraints. Here, buildings and communities optimize their energy exchange strategies independently, aiming to maximize individual benefits. Pricing mechanisms such as C2C, B2B, and B2C prices are determined based on decentralized decision-making.

Chapter 5, on the other hand, integrates network constraints by incorporating the Distribution System Operator (DSO), which performs Optimal Power Flow (OPF) to determine Locational Marginal Prices (LMPs). This chapter also introduces network utilization charges based on LMP and accounts for renewable energy uncertainties, which were not considered in Chapter 4. Additionally, a cooperative game-theoretic approach is used instead of a non-cooperative one, allowing participants to collaborate for improved cost allocation and efficiency.

Thus, while both chapters deal with P2P energy trading, their methodologies, objectives, and constraints are fundamentally different. The candidate hopes this explanation clarifies the examiner's query.

> **15**: **Q5_2: Is** the problem formulation in sec 5.2.2, the same in chapters 4 and 5? Same Game theory is described in sec 5.3.1

Response: The candidate extends her thanks to the examiner for this question. The building-level problem formulation in Section 5.2.2 is indeed the same as in Chapter 4, as both chapters consider the same optimization framework at the individual building level. However, the overall approach and methodology differ significantly.

Chapter 4 employs a non-cooperative game-theoretic approach, where buildings optimize their strategies independently without considering network constraints.

Chapter 5 introduces network constraints through the DSO performing OPF to determine LMP, along with network utilization charges and renewable uncertainties, which were not included in Chapter 4. Additionally, it applies a cooperative game-theoretic approach instead of a non-cooperative one, allowing participants to collaborate for better cost allocation and system efficiency.

Regarding Section 5.3.1, while both chapters discuss game theory, the type of game-theoretic approach used is different. Chapter 4 uses a non-cooperative game, whereas Section 5.3.1 in Chapter 5 discusses a cooperative game, making their applications distinct. The candidate hopes this explanation clarifies the examiner's query.

> **16**: **Q5_3: Is** the work on P2P Energy Exchange or P2P Energy Trading related to Virtual Power Plant (VPP)?

Response: The candidate sincerely thanks the examiner for the comment. The concept of P2P energy exchange/trading is indeed related to a Virtual Power Plant (VPP), particularly through the formation of virtual communities. However, there are key differences in their roles and functionalities.

- In this work, virtual communities act as aggregated entities where buildings share energy among themselves. Unlike a traditional VPP that primarily functions as a virtual generator, a virtual community can sometimes act as a virtual load, depending on the energy availability and demand.
- Both VPPs and virtual communities involve energy management and optimization, and both utilize Battery Energy Storage Systems (BESS) to enhance flexibility and reliability. However, in a VPP, the energy exchange is typically coordinated by a central operator, while in a P2P framework, decision-making remains more decentralized, allowing prosumers to interact directly.

- Virtual Communities (VCs) in P2P trading share energy among themselves, allowing prosumers within the community to trade energy flexibly. VPPs, on the other hand, do not enable direct energy sharing among participants. Instead, a VPP aggregates the energy resources and optimally dispatches them to the grid as a single entity.

Thus, while virtual communities share some characteristics with VPPs, particularly in energy aggregation and storage, their fundamental difference lies in their operational flexibility—virtual communities can act as both virtual power plants and virtual loads, whereas a VPP primarily functions as a power generator. The candidate hopes this explanation clarifies the examiner's query.

17: **Q5_4**: **Are** the results of chapters 4 and 5 the same?

Response: The candidate is gratefull to the examiner for the comment. The results of Chapters 4 and 5 are not the same due to differences in the game-theoretic approach and network constraints.

Chapter 4 uses a non-cooperative game without network constraints. In this case, each participant optimizes its own strategy independently, leading to a Nash equilibrium, which is not necessarily the optimal solution from a system-wide perspective. Also, due to the lack of network constraints in Chapter 4, the energy exchange is purely based on economic incentives among prosumers.

Chapter 5 applies a cooperative game with network constraints, where participants collaborate to achieve a socially optimal solution. The equilibrium in this case corresponds to an optimal point, ensuring better cost efficiency and power distribution. In Chapter 5, network constraints (e.g., line limits, voltage constraints, Locational Marginal Pricing (LMP)) are incorporated, affecting both power flows and cost allocation.

As a result, there is a slight variation in power and cost results between the two chapters, reflecting the difference between unconstrained decentralized trading (Chapter 4) and constrained, optimized trading (Chapter 5). Thus, while both chapters address P2P energy trading, their methodologies lead to different equilibrium conditions and, consequently, different results. The candidate hopes this explanation clarifies the examiner's query.

18: **Q7_1: Where** is the **'Real Time Scenario'**

Response: The candidate expresses sincere gratitude to the examiner for this insightful query regarding the real-time scenario in the thesis.In the proposed framework, day-ahead scheduling forms the baseline for real-time operations. The day-ahead schedule is determined based on forecasted data for renewable generation, load demand, and market prices. These schedules optimize energy transactions, including

- Day-ahead schedules calculate building-to-building (B2B), building-to-community

(B2C), and community-to-community (C2C) energy exchanges.

- Charging and discharging schedules are optimized to store surplus renewable energy during off-peak hours and discharge it during peak demand periods.
- Adjusting load profiles in response to forecasted demand patterns.
- The schedule determines the quantity of energy imported from or exported to the utility grid.

In real-time operations, these day-ahead schedules act as baseline references but are adjusted dynamically to account for deviations caused by uncertainties in renewable generation or load demand. The real-time adjustments include

- Modifying charging/discharging schedules based on real-time renewable generation and demand fluctuations.
- Balancing discrepancies between scheduled and actual P2P transactions by importing/exporting energy from/to the grid.

Practical Example: Aggregated Profiles of Virtual Community 1 To illustrate this integration, the aggregated load, renewable generation, BESS charging/discharging, and grid exchange power profiles for Community 1 are analyzed as shown in Figure8. These graphs depict these profiles over a 24-hour period.

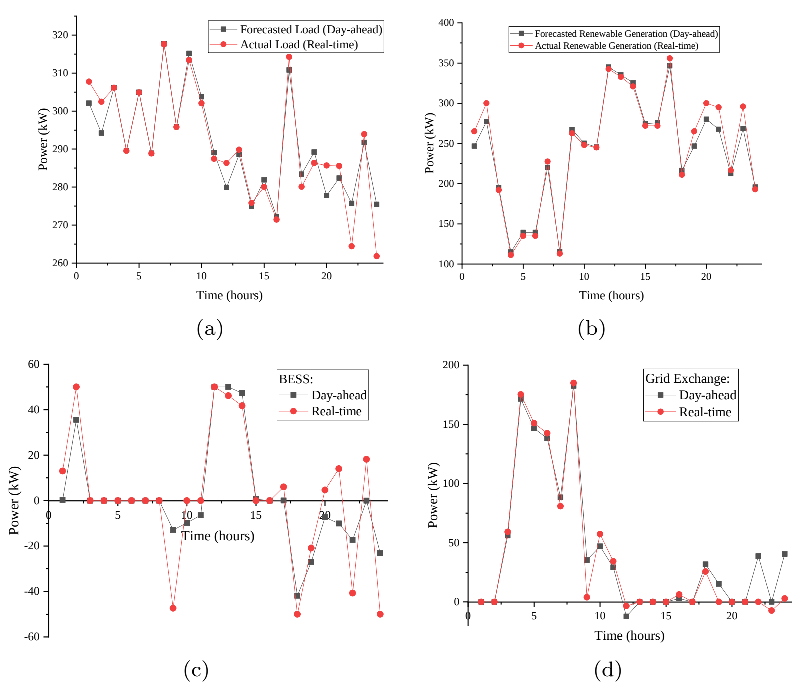

Figure 8: Practical Example: Aggregated Profiles of Virtual Community 1 during day-ahead and real-time operation (a) Load Profile, (b) Renewable generation, (c) BESS charging-discharging power profile, and (d) Grid exchange power profile

Day-Ahead Scheduling: During periods of high renewable generation (e.g., midday)(Figure 8(b)), surplus energy is stored in the BESS (Figure 8(c)) or traded with other communities/buildings via P2P transactions. During peak demand hours (around 1700 hours as shown in (Figure 8(a))), stored energy is discharged from the BESS to meet local demand or traded with other participants. Grid imports and exports are minimized as shown in Figure 8(d).

Real-Time Adjustments: The P2P (B2B and C2C) power exchanges are made fixed to the day-ahead values. If actual renewable generation (Figure 8(b)) exceeds forecasts, additional surplus energy is either stored in the BESS or exported to the grid. In case of lower-than-expected generation, additional energy is imported either from BESS (Figure 8(c)) or from the grid (Figure 8(d)).
The graphs (Figure 8) shows how day-ahead schedules align with forecasted trends while real-time adjustments ensure deviations are managed effectively. This integration ensures that day-ahead schedules provide a baseline while real-time adjustments maintain operational efficiency and reliability of the system. The practical example using virtual community 1's aggregated profiles highlights how this dual-stage approach optimizes energy management in a decentralized P2P trading framework. The candidate appreciates this opportunity to elaborate on this critical aspect of the thesis and believes that this explanation clarifies the integration of day-ahead and real-time scheduling effectively. This description has been added to the thesis in chapter 7 section 7.3.3.

Chapter-wise Comments on the Thesis

Chapter-1: Introduction

> **1**: This chapter provides the introduction to the topic of Energy communicates in Distribution Systems and Smart Buildings.

Response: The candidate acknowledges that Chapter 1 (Introduction) provides an overview of the topic of energy communities in distribution systems and smart buildings. This chapter sets the stage for the research by discussing the importance of energy management, the role of smart buildings, and the integration of distributed energy resources (DERs) in active distribution networks. The candidate expresses her gratitude for the examiner's recognition of the introductory context and believes that this chapter successfully introduces the key concepts necessary for understanding the subsequent chapters.

> **2**: Local Energy Trading Techniques, like **Pool Based** and **Peer Based** Energy Trading are discussed.

Response: The candidate acknowledges the examiner's observation regarding the discussion of local energy trading techniques, including pool-based and peer-based energy trading, in the introduction. These techniques serve as foundational concepts in the research, as they highlight the different approaches to energy exchange within localized systems.

> **3**: Several Objectives, namely, **TWELVE** in number, are listed in sec 1.6. The objectives considered are **too many**. The objectives are to be rewritten with a minimum of **TWO** and a Maximum of **THREE** objectives only.
> **To Design**
> **To Develop**
> **To Implement**

Response: The candidate sincerely thanks the examiner for the valuable feedback. The candidate understands that twelve objectives might appear excessive for a research thesis, and agrees that a more concise set of objectives could better reflect the core focus of the work. Following the examiner's suggestion, the candidate proposes the following revised objectives with a focus on design, development, and implementation:

- To design a decentralized P2P energy-sharing framework that integrates BESS and addresses uncertainties in renewable generation, ensuring the preservation of network constraints and enabling secure energy exchange among buildings. The framework also incorporates the concept of virtual communities (VCs), where buildings on the same bus are grouped to reduce the computational burden and communication complexity in large systems.
- To develop a game-theoretic-based algorithm for optimizing energy trading mechanisms (including B2B, B2C, and P2P transactions) within virtual communities. The algorithm aims to ensure fair pricing, privacy preservation, and efficient handling of network constraints. The concept of virtual communities is key here, as it helps aggregate energy exchanges within a bus, reducing the number of participants and simplifying transactions while maintaining the integrity of network operations.
- To implement a practical real-time and day-ahead energy trading system that incorporates dynamic pricing mechanisms, network usage charges, and cloud-based communication, facilitating secure data sharing with the Distribution System Operator (DSO) for effective coordination. The virtual communities concept is integral to this implementation, ensuring that energy exchanges are managed efficiently across multiple geographical locations while addressing privacy and scalability concerns.

These three objectives encapsulate the core design, development, and implementation aspects of the thesis, aligning with the broader research goal of creating an efficient and practical P2P energy trading framework. In the thesis also, this has been incorporated as shown below.

1.6 Objectives and Scope of the Thesis

The main goal of this research is to design, develop, and implement a decentralized peer-to-peer (P2P) energy-sharing framework that integrates Building Energy Storage Systems (BESS) while addressing renewable generation uncertainties and maintaining distribution network constraints. The objectives of this thesis are as follows.

- To design a decentralized P2P energy-sharing framework that integrates BESS and addresses uncertainties in renewable generation, ensuring the preservation of network constraints and enabling secure energy exchange among buildings. The framework also incorporates the concept of virtual communities (VCs), where buildings on the same bus are grouped to reduce the computational burden and communication complexity in large systems.
- To develop a game-theoretic-based algorithm for optimizing energy trading mechanisms (including B2B, B2C, and P2P transactions) within virtual communities. The algorithm aims to ensure fair pricing, privacy preservation, and efficient handling of network constraints. The concept of virtual communities is key here, as it helps aggregate energy exchanges within a bus, reducing the number of participants and simplifying transactions while maintaining the integrity of network operations.
- To implement a practical real-time and day-ahead energy trading system that incorporates dynamic pricing mechanisms, network usage charges, and cloud-based communication, facilitating secure data sharing with the Distribution System Operator (DSO) for effective coordination. The virtual communities concept is integral to this implementation, ensuring that energy exchanges are managed efficiently across multiple geographical locations while addressing privacy and scalability concerns.

The scope of this thesis includes the integration of both intra- and inter-bus P2P energy sharing. The proposed framework employs virtual communities (VCs) to reduce the computational complexity associated with increasing participants, ensuring scalability and efficiency. This research also addresses critical issues related to participant privacy, data security, and the feasibility of applying network constraints in large-scale systems.

The candidate hopes this revision aligns with the examiner's expectations.

> **4**: The thesis organization has **too many chapters**, eight in number. Five chapters are more than sufficient.

Response: The candidate thanks the examiner for his valuable feedback. While the candidate understands the examiner's concern about the number of chapters and the apparent overlap, the candidate would like to clarify that each chapter presents distinct concepts and methodologies that contribute to the overall analysis of Peer to Peer (P2P), Building to Building (B2B), Building to Community (B2C), and Community to Community (C2C) models. Each chapter addresses a unique aspect of the problem, with careful attention to the different contexts and applications as given in Table 10.

Table 10: Different Concepts Involved in Various Chapters of this Thesis

Concepts	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Peer-to-Peer Energy Trading	✓	✓	✓	✓	✓
Multi-community	×	✓	✓	✓	✓
Renewable Uncertainty	✓	×	✓	✓	✓
Game involved	Cooperative Game (Nash Bargaining)	Non-Cooperative Game	Cooperative Game (Nash Bargaining)	Cooperative Game (KS Bargaining)	Cooperative Game (KS Bargaining)
Network Contraints	×	×	✓	✓	✓
Active participation of DGs	×	×	×	✓	✓
Analysis of the effect of DGs' participation actively and marginal cost basis on LMPs	×	×	×	✓	×
Cost analysis of effect of network constraints in Day-ahead scheduling	×	×	×	×	✓
Real-time load scheduling	×	×	×	×	✓
Real-time BESS scheduling	×	×	×	×	✓

5: Fig 1.1 is good. This chapter provides a good literature review of the topic.

Response: The candidate is pleased that the chapter and its associated figure effectively presented the key concepts related to the topic and provided a comprehensive overview of the literature.

6: However, literature review on peer to peer energy trading should be supported by block diagrams illustrating the example.

Response: The candidate is grateful to the examiner for this suggestion. Following image Figure 10, Figure 9 and Figure 11 has been incorporated in the thesis along with its description in chapter 1.

The transition for the power system from conventional to modern can be seen from Figure 10.
The main elements of P2P energy trading can be seen in Figure 9.
The illustration showing the difference beetween pool and peer-to-peer energy trading is shown in Figure 11.

Chapter-2: Preliminary Methodologies

1: This chapter title 'Preliminary Methodologies' provides information on 2M Point Estimation Method for Stochastic Modelling of Renewable Energy Generation.

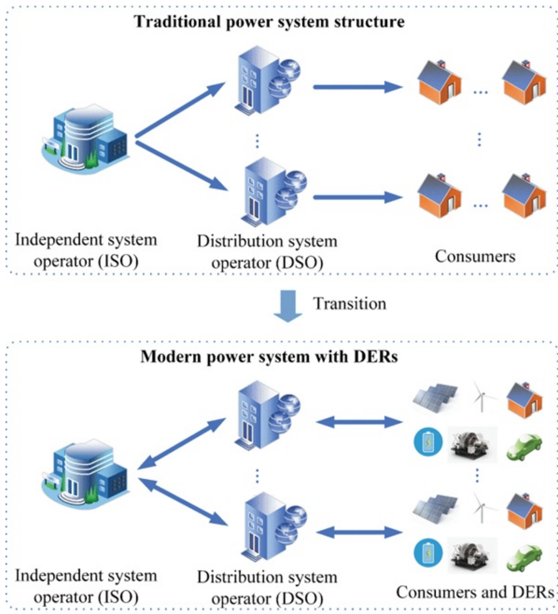

Figure 9: Power System Transition Diagram.[24]

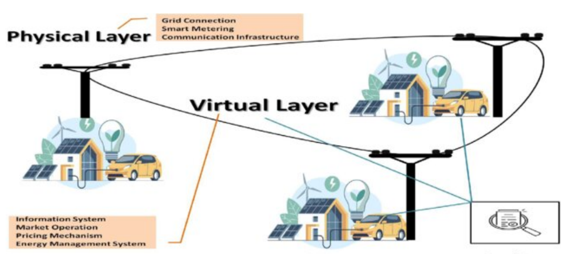

Figure 10: Elements of P2P Energy trading[25]

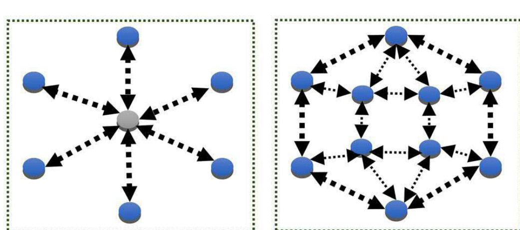

Figure 11: Pool based and Peer-to-peer based energy trading[26]

Response: The candidate expresses her gratitude for the examiner's recognition of the content provided in this chapter.

> **2**: The title needs to be changed.

Response: The candidate sincerely thanks the examiner for this question and the title of this chapter has been changed to "Peer-to-Peer Energy Trading Frameworks and Methodologies: An Overviews".

> **3**: Game Theory is introduced in sec 2.3. This is too theoretical.

Response: The candidate agrees with the examiner's observation that the concepts in this chapter are more theoretical. However, this chapter serves as a prerequisite that introduces simple basic theory, formulas, and equations which are essential for the problem formulation in the subsequent chapters. The purpose of this section is to establish a solid theoretical foundation, which is then applied in later chapters to develop and analyze the P2P energy trading models. Without these fundamental concepts, the problem cannot be properly addressed in the practical context of the thesis.

> **4**: Instead, Peer to Peer Energy Trading should have been discussed

Response: The candidate understands the importance of introducing P2P energy trading at this stage to provide a clearer context for the reader. Therefore, in the next chapter, the candidate has introduced a simplified system consisting of a single virtual community to illustrate the P2P energy trading problem. This will provide a more practical and accessible understanding of how P2P energy trading operates, before delving into the more complex game-theoretic models in subsequent sections. This adjustment will ensure that the thesis flows logically from the theoretical foundations to the practical application of P2P energy trading.

Chapter-3: Stochastic Peer-to-Peer Energy Trading Model

> **1**: This chapter describes the 'Stochastic Peer to Peer Energy Trading Model

Response: The candidate expresses her gratitude for the examiner's observations.

2: **Q3_1: Why** is there a need to consider **Stochastic Model**? A **Deterministic Model** should be considered and introduced first and discussed in detail.

Response: The candidate agrees with the examiner that a deterministic model should be considered and introduced first in detail. The reasoning behind placing Chapter 3 (the stochastic model with a single community using a cooperative game) before Chapter 4 (the deterministic model with multiple communities using a non-cooperative game) is based on the need to first establish a simpler, more controlled scenario before moving to a more complex and expansive model.

The stochastic model in Chapter 3 introduces key concepts in a single-community setup, allowing for a foundational understanding of energy trading dynamics under uncertainty. By starting with this model, the candidate wanted to set a base for how the cooperative game framework operates in a less complex environment, which can be easily understood before extending these ideas to multiple communities in Chapter 4.

The more complex deterministic model in Chapter 4 then builds upon this foundation by considering a larger-scale, multi-community setup and a non-cooperative game, where participants are independent and seek to optimize their own outcomes. This progression from a simpler to a more complex model aligns with the goal of guiding the reader step-by-step through the concepts.

The candidate hopes this clears up the rationale for the ordering and appreciates the feedback on this matter.

3: A **Building to Building (B2B)** framework is introduced in sec 3.1 and fig 3.1.

Response: The candidate expresses her gratitude for the examiner's observations.

4: **Q3_2:** Is the **B2B Energy Trading** the same as **P2P Energy Trading**?

Response: The candidate sincerely thanks the examiner for the comment and would like to clarify the distinction between B2B (Building-to-Building) Energy Trading and P2P (Peer-to-Peer) Energy Trading. While both B2B and P2P energy trading involve the exchange of energy between entities, they differ in their scope and structure.

P2P energy trading typically refers to the direct energy transactions between independent participants, which can be individuals, buildings, or communities. In this thesis, peers trade energy based on their individual needs and available resources, facilitated through decentralized platforms.

On the other hand, B2B energy trading is more specific to energy exchanges between buildings, which can be part of a larger distribution network. In this case, energy trading occurs within a defined group of buildings, with a focus on optimizing energy consumption and reducing costs within that group.

While both models share similarities in facilitating energy transactions, B2B energy trading can be seen as a subset of P2P energy trading, with a narrower focus on building-to-building interactions rather than broader peer-to-peer exchanges. The candidate hopes this distinction clarifies the differences between B2B and P2P energy trading and appreciates the examiner's inquiry.

5: **Q3_3:** **Where** is the single line diagram (**SLD**) of the **B2B** energy trading diagram?

Response: The candidate sincerely thanks the examiner for this question. The single line diagram (SLD) of the B2B energy trading diagram is shown below (Figure 12). The buildings are grouped into virtual communities as can been from this diagram. This figure has been added in chapter 3 as Figure 3.2.

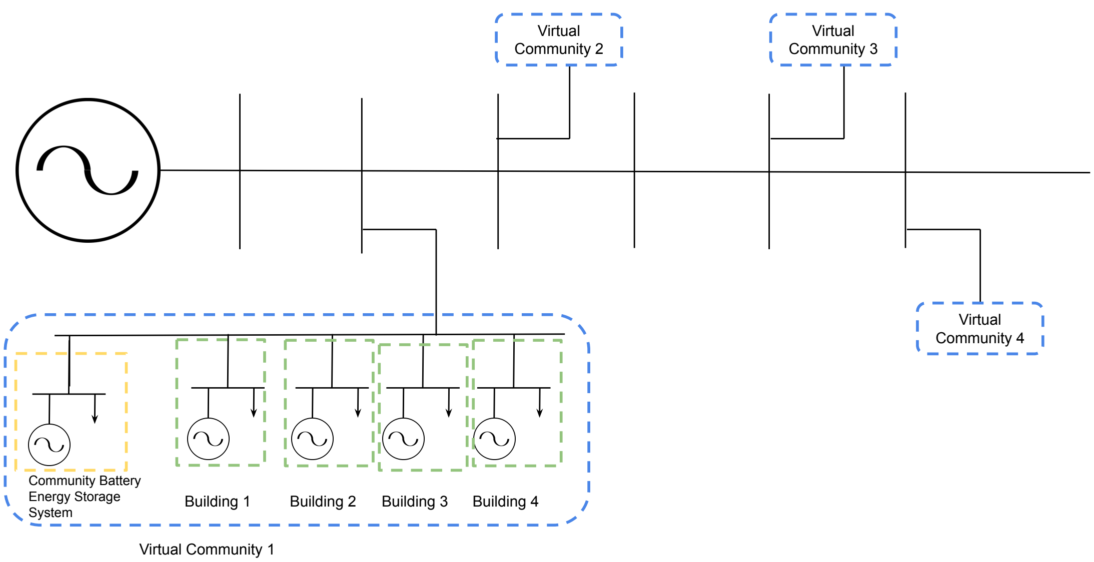

Figure 12: Single line diagram (SLD) for the system

6: **Q3_4:** In Energy trading using B2B, more information on **How** much power and energy sold/purchased OR sell bids and buy bids are to be provided.

Response: The candidate sincerely thanks the examiner for the comment. The information regarding B2B energy sharing is already provided in the thesis within Figure 3.3(A) (in the thesis), which is positive when building buys from others; else it is negative. The respective incentives and hourly prices are shown in Table 3.4 (in the thesis) and Figure 3.3(B) (in the thesis), respectively. The candidate hopes this clarifies the matter and appreciates the examiner's attention to this aspect of the thesis.

7: The simulation results in sec 3.4 show the load profile

Response: The candidate expresses her gratitude for the examiner's observation. In section 3.4 (in the thesis), the simulation results have been discussed which starts by specifying all the inputs taken in this model such as the load profile.

8: **Q3_5**: Page 35, the legend for the Algorithm I is missing. This needs to be provided. **What** does this algorithm do? There is no information.

Response: The candidate sincerely thanks the examiner for the comment. Regarding the missing legend for Algorithm 1 on page 35, the candidate acknowledges the oversight and will add a clear description of the algorithm in the legend to ensure that its purpose and functionality are well understood.

To clarify, Algorithm 1 outlines the steps for implementing the P2P energy-trading framework using a cooperative game approach combined with the ADMM (Alternating Direction Method of Multipliers) for optimization. The algorithm facilitates the optimal distribution of energy among participants in the network while considering their individual energy demands and generation capacities. The cooperative game approach ensures that the participants work together to maximize the overall benefit, while the ADMM is used to efficiently solve the optimization problem by decomposing it into smaller subproblems that can be solved iteratively.

The candidate will ensure that this explanation is included in the legend in the thesis for Algorithm 1, to provide a complete understanding of the algorithm's function. This has been modified in the thesis as follows: Algorithm 1: Algorithm for optimizing P2P energy sharing using a cooperative game approach and ADMM to distribute energy efficiently among participants by solving the optimization problem iteratively.

9: **Q3_6:** Table 3.1, **can** each building (build 1, 2, 3) be considered as a node? An equivalent circuit of the same B2B should be provided as a 3 bus/node system. Analysis should be performed. Similar with table 3.3.

Response: The candidate is thankful to the examiner for their insightful ques-

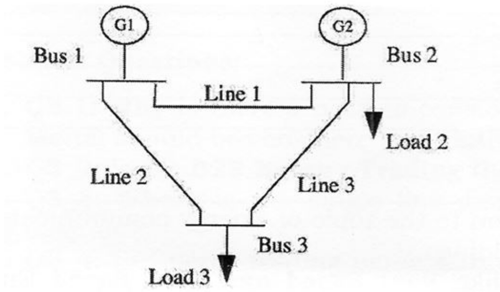

Figure 13: Given by examiner for comment 9

tion. Yes, each building in the B2B energy trading framework can be considered as a node in the equivalent circuit. This is because

- Each building has its own load, renewable energy generation, and potentially a battery energy storage system (BESS), making it a distinct entity in terms of power flow.
- The interaction between buildings (energy exchange) can be represented as power flows between nodes in an electrical network.
- The community battery energy storage system (CBESS) acts as an additional node that interacts with all buildings.

The equivalent circuit can be drawn as shown in Figure 14. The introduction

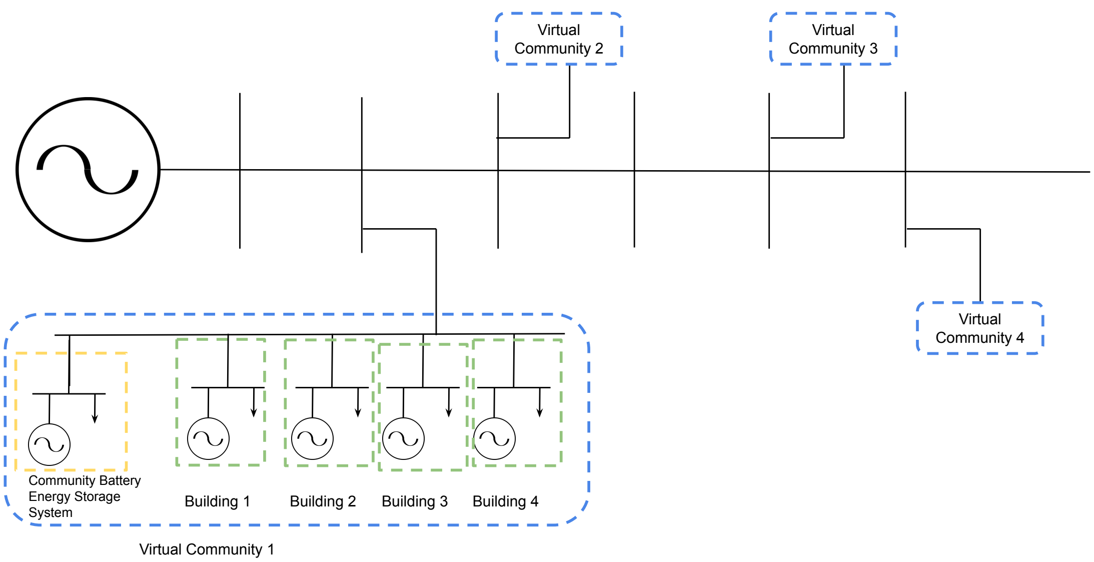

Figure 14: Electrical Network Analogy

of B2B energy trading significantly reduces costs for all participants by enabling surplus renewable energy to be shared among buildings. The CBESS further enhances cost savings by storing surplus energy during low-demand periods and discharging it during peak demand. This equivalent circuit representation effectively models the B2B energy trading framework, with each building considered as a node. This abstraction highlights the interactions between buildings and their shared resources (CBESS), enabling detailed analysis of power flows and cost optimization. The candidate appreciates this opportunity to clarify and enhance the understanding of the proposed framework. This figure has been added in chapter 3 as Figure 3.2 and description in section 3.4.

10: Fig 3.1(b), should be shown as a line chart instead of a bar chart.

Response: The candidate sincerely thanks the examiner for this question. The bar graph from Fig.3.1(b) has been modified to line chart as shown in Figure 15

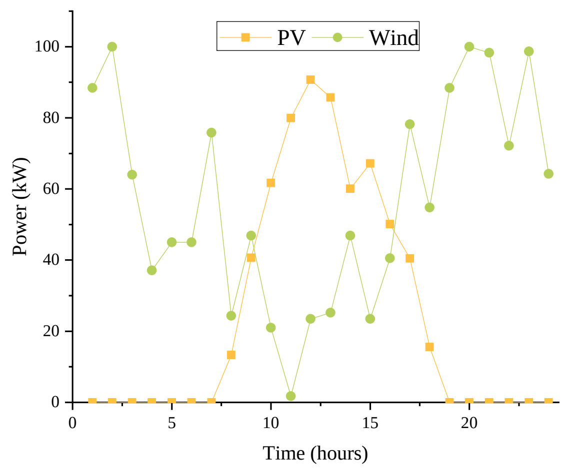

Figure 15: Data for renewable generation of the buildings.

11: **Q3_7:** Fig 3.3 (a), 3.4(a), 3.4(b), **why** is the power from buildings negative? **Are** the buildings prosumers?

Response: The candidate sincerely thanks the examiner for this question. The buildings in the study are indeed prosumers, meaning they can both consume (load) and generate (renewable resources) energy. When buildings generate excess energy, they either sell it back to the grid or share it with other peers.

The reason the power from buildings appears negative is due to the convention used in the formulation. A negative power value indicates that the building is exporting (selling) energy, while a positive value represents energy consumption. This convention is commonly used in energy trading models to distinguish between energy generation and consumption clearly.

The candidate hopes this clarification addresses the examiner's query.

12: Fig 3.3 (b), where is the P2P corresponding to the varying electricity of prices? IS B2B the same as P2P?

Response: The candidate thanks the examiner for this question. The power profiles in both cases are nearly identical. Therefore, to avoid redundancy, they are presented only once. In fact, the total cost is also almost identical. The main difference lies in the execution time of both the methods. The execution time for energy scheduling with the incentive mechanism is 102.730 seconds, whereas with the hourly-pricing mechanism, the execution time for energy scheduling is 150.675 seconds.The incentive-based mechanism is comparatively faster and can be used when hourly rates are not required.

In chapter 3, buildings exchange energy with other buildings only as a peer-to-peer energy exchange. Therefore, in this context, building-to-building (B2B) and P2P energy exchange are same.

Chapter-4: A Scalable Peer-to-Peer Energy Trading Model

1: This chapter 4 describes a scaled down P2P Energy Trading Model

Response: The candidate expresses her gratitude to the examiner for their valuable feedback. In chapter 4, the grouping of buildings into virtual communities is a deliberate approach to scaling down the Peer-to-Peer (P2P) energy trading model while preserving its core principles. This method ensures a balance between computational efficiency and practical implementation by reducing the number of direct transactions while maintaining the benefits of localized energy trading.

2: **Q4_1:** Fig 4.1 shows the P2P, B2B and B2C respectively. Is the **Energy Sharing** the same as **Energy Trading**?

Response: The candidate sincerely thanks the examiner for the question. In Fig. 4.1 (in the thesis), the P2P energy sharing framework includes Building-to-Building (B2B), Building-to-Community (B2C), and Community-to-Community (C2C) interactions, all of which fall under the broader concept of P2P energy trading.

Regarding the distinction between energy sharing and energy trading, while both involve the exchange of energy among participants, energy trading typically refers to transactions where energy is bought and sold with associated pricing mechanisms, whereas energy sharing can imply a cooperative exchange without strict financial transactions. However, in the context of this work, the terms are used interchangeably since the framework considers both cooperative and market-based mechanisms for energy exchange. The candidate hopes this explanation clarifies the examiner's query.

> **3**: This chapter describes more information on Building Energy Management (BEM) with emphasis on B2B and B2C than Power Networks.

Response: The candidate expresses her gratitude for the examiner's observations.

> **4**: Sec 4.3 provides the Methodology for game theory for energy trading in buildings using **ADMM**. The scholar should provide information on the formulation of Maximize / Minimize an Objective Function like Social Welfare of Profit maximization, etc.

Response: The candidate expresses her gratitude for the examiner's observations. In this chapter, non-cooperative game is employed for P2P energy transactions among the buildings. For calculating the Genarlised Nash Equilibrium of the problem, a regularised Nikaido-Isoda-function (also known as NI-function) is used.[27] This NI function quantifies the improvement a player could achieve by unilaterally changing its strategy while keeping other players' strategies fixed. Equation 4.27 (in the thesis) maximizes the deviation potential of each participant in the game by checking whether a better strategy (q) exists compared to the current one (z). At equilibrium, the function value approaches zero, meaning that no participant can improve its objective function unilaterally, indicating that the Generalized Nash Equilibrium (GNE) is reached.

Indirectly the objective function aims to find the best strategy that will result in minimum cost irrespective of opponent's strategy. The candidate hopes that this will help in clarifying the examiner's query. This description has been added to the thesis in chapter 4 in section 4.3.1.1

> **5**: **Q4_2**: What is the significance of Eqn 4.27? What is being maximized.

Response: The candidate expresses her gratitude to the examiner for such an insightful question. Equation 4.27(in the thesis) is given by the following.

$$\tau(z, q) = \arg max_{q \in (\gamma_b, \gamma_c)} \phi(z, q). \tag{25}$$

Here $\phi(z, q)$ is defined by the following.

$$\phi(z, q) = \sum_{p}^{players} [C_F(z_p, z_{-p}) - C_F(q_p, z_{-p})] - \frac{\delta}{2} ||z - q||_2^2. \tag{26}$$

[27]Facchinei and Kanzow, "Generalized Nash equilibrium problems".

The above function denotes the total gains of player p if it switches from its current strategy z_p to q_p regardless of other players' strategies. Here δ is a known parameter. To find the Genarlised Nash Equilibrium, a regularised Nikaido-Isoda-function (also known as NI-function) is used.[28] In this case, $\phi(z, q)$ is the NI function, where q has the same dimensions as z. The NI function is a fundamental tool for solving generalized Nash equilibrium problems (GNEPs) in game theory. It quantifies the improvement a player could achieve by unilaterally changing its strategy while keeping other players' strategies fixed.

Equation 4.27 (in the thesis) (25) maximizes the deviation potential of each participant in the game by checking whether a better strategy (q) exists compared to the current one (z). At equilibrium, the function value approaches zero, meaning that no participant can improve its objective function unilaterally, indicating that the Generalized Nash Equilibrium (GNE) is reached.

Thus, Equation 4.27 (in the thesis) is crucial for reformulating and solving the GNEP, ensuring the stability and convergence of the non-cooperative game. The candidate hopes this explanation clarifies the examiner's query. This description has been added to the thesis in chapter 4 in section 4.3.1.1

6: **Q4_3: How** and **Why** is Game theory suitable and applicable for P2P/B2B/ B2C Energy Trading/ Energy Sharing. It is not clear Under what circumstances is game theory is found to be suitable?

Response: The candidate expresses her gratitude to the examiner for this insightful question. Game theory is suitable and applicable for C2C, B2B, and B2C energy trading/sharing because these interactions involve multiple decision-making entities (buildings and communities) that strategically optimize their energy exchange based on their individual objectives while considering the actions of others.

The Game Theory is suitable for such interaction due to the following reasons.

- Decentralized Decision-Making: In P2P energy trading, prosumers act independently, making decisions about selling, buying, or sharing energy. Game theory provides a framework to model their strategic interactions.
- Optimization of Benefits: Each participant aims to maximize its own benefit (e.g., minimizing costs or maximizing revenue), and game theory helps determine equilibrium strategies where no participant has an incentive to deviate.
- Fair and Efficient Energy Allocation: Cooperative game theory ensures that participants can form coalitions to share energy in a mutually beneficial way, while non-cooperative game theory helps model competitive scenarios where prosumers act individually.

[28] Facchinei and Kanzow, "Generalized Nash equilibrium problems".

- Market Stability and Convergence: Game theory ensures that energy transactions reach a stable state (equilibrium), where supply and demand are balanced efficiently

In general, under the following circumstances, Game Theory is found to be suitable.

- Multiple Independent Decision Makers Exist: In P2P/B2B/B2C trading, buildings and communities act as independent decision-makers, making it necessary to model their interactions strategically.

- Strategic Behavior Influences Outcomes: Each participant's decision depends on the decisions of others, making traditional optimization approaches less effective.

- Market-Based and Cooperative Energy Sharing Exists: Both competitive (non-cooperative) and collaborative (cooperative) scenarios can be modeled using game theory.

- Dynamic and Decentralized Systems Are Involved: When energy supply, demand, and pricing are dynamic, game theory provides adaptive and scalable solutions.

In this thesis, game theory is applied to model both cooperative and non-cooperative interactions in various P2P energy-sharing frameworks, ensuring efficient energy distribution and market stability. The candidate hopes this explanation clarifies the examiner's query. This description has been added to the thesis in chapter 2 section 2.6.

> **7**:Sec 4.3.1.2, and Fig 4.2, the decentralized approach.

Response: The candidate expresses her gratitude to the examiner for this question. Section 4.3.1.2 of the thesis describes the use of the Alternating Direction Method of Multipliers (ADMM) for implementing a decentralized approach. However, Figure 4.2 presents the complete algorithm for determining the Generalized Nash Equilibrium of the model. According to the diagram, the process begins with level 1 and level 2 optimizations. Once these optimizations converge through ADMM, the next step involves verifying the convergence of the strategies.

> **8**:**Q4_4:** The Algorithm 2 in page 52, should have a legend. What does this algorithm describe?

Response: The candidate sincerely thanks the examiner for the comment. The legend for Algorithm 2 on page 52 will be provided to clearly describe its purpose.

Algorithm 2 presents the P2P energy sharing framework using a non-cooperative game and ADMM (Alternating Direction Method of Multipliers). In this framework, buildings are grouped into virtual communities, and energy trading occurs in B2C, B2B, and C2C settings. The algorithm searches for the optimal energy trading strategy for each participant irrespective of the strategies of others, aligning with the principles of a non-cooperative game. ADMM is used to efficiently solve the decentralized optimization problem by breaking it into smaller subproblems that each participant can solve iteratively while maintaining privacy. This ensures computational efficiency and convergence to an optimal trading strategy.

The candidate will ensure that this explanation is included as the legend for Algorithm 2 in this thesis to improve clarity in the following way.

Algorithm 2: Algorithm for P2P energy sharing using a non-cooperative game and ADMM, where buildings in virtual communities optimize their energy trading strategies independently.

9: All of these algorithms can be provided in the appendix with complete description of its function.

Response: The candidate acknowledges the examiner's suggestion to include all the algorithms in the appendix with a complete description of their functions. However, these algorithms are integral to explaining the step-by-step process of the proposed framework. Placing them within the main chapters ensures clarity in understanding the methodology and its implementation. Moving them to the appendix may disrupt the logical flow of explanation and make it difficult for the reader to follow the problem formulation and solution approach seamlessly. Therefore, the algorithms are retained within the respective chapters to maintain coherence in presenting the research work.

10: **Q4_5:** Sec 4.3.2.1, What is C2C Price? How is it different from B2B and P2P prices?

Response: The candidate sincerely thanks the examiner for the comment. The C2C price refers to the P2P energy exchange price between different virtual communities, whereas B2B prices correspond to P2P energy trading at the building level. The key differences are as follows.

- C2C Price (Community-to-Community Price): This is the price determined for energy trading between different virtual communities. It is calculated first to establish the cost of energy exchange at the community level.
- B2B Price (Building-to-Building Price): This is the energy trading price between individual buildings within the same community. It governs the direct exchange of energy between prosumer buildings.

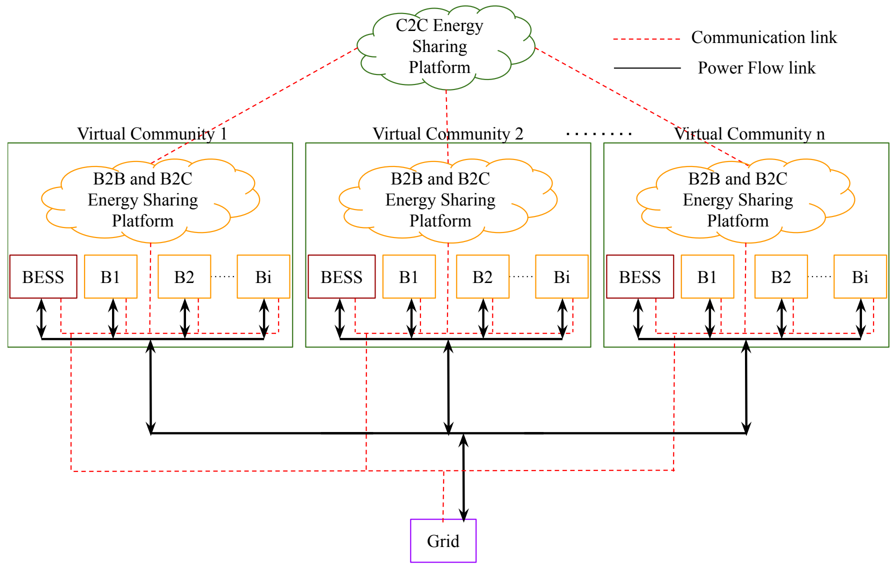

Figure 16: Illustration for P2P Energy Trading

- P2P Price (Peer-to-Peer Price): This is a general term encompassing all decentralized energy trading interactions, including B2B, B2C, and C2C.

The pricing structure follows a hierarchical approach. C2C Price is calculated first to determine the cost of energy exchange between virtual communities. The total cost of each community is then divided among its buildings using the B2C price (Building-to-Community Price). The B2B price is incorporated along with other cost factors to determine the total cost of each building. This pricing mechanism ensures fair and efficient cost distribution across different levels of energy exchange. The candidate hopes this explanation clarifies the examiner's query. This description has been added to the thesis in chapter 4 section 4.3.2.

11: The block diagrams illustrated the working of P2P, B2B. B2C and C2C are to be provided.

Response: The candidate is grateful to the examiner for this suggestion. Figure 16 has been added to the thesis in chapter 4 as Figure 4.4 illustrating the working of the P2P energy trading which includes B2B, B2C, and C2C energy trading.

12: Fig 3.3 is good with levels 1 and 2. How are P2P, C2C and B2B are related and linked? Are there any common tasks and exchange of information?

Response: The candidate acknowledges the examiner's query regarding the relationship and linkage between P2P, C2C, and B2B energy exchanges. It seems that the examiner might be referring to Fig. 4.3 rather than Fig. 3.3.

The P2P energy exchange framework inherently includes B2B, B2C, and C2C transactions. In Fig. 4.3, the scheduling of P2P energy occurs first, encompassing all three types of exchanges—B2B, B2C, and C2C. Based on this scheduled energy exchange, the corresponding prices are determined. Since C2C energy exchange occurs between different communities, the first step is to determine the C2C price based on the exchanged C2C power. Once the C2C price is established, the B2B and B2C energy exchange prices are computed based on scheduled power transactions and the C2C price. Regarding optimization levels, Level 1 represents building-level optimization, where each building optimizes its energy transactions, while Level 2 represents community-level optimization, where communities manage their internal and external energy exchanges.

13: A representative **circuit** or **network diagram** of the information provided in table 4.5 regarding C1, C2, C3; B1, B2, B3 with SPV, WPG, BESS are to be provided. An electrical network analogy of the B2B, P2P, C2C is to be provided.

Response: The candidate is thankful to the examiner for their insightful question. The respective electrical network analogy of the information in table 4.5 regarding C1, C2, C3: B1, B2, B3 with SPV, WPG, BESS in terms of B2B, P2P, C2C is given in Figure 17.

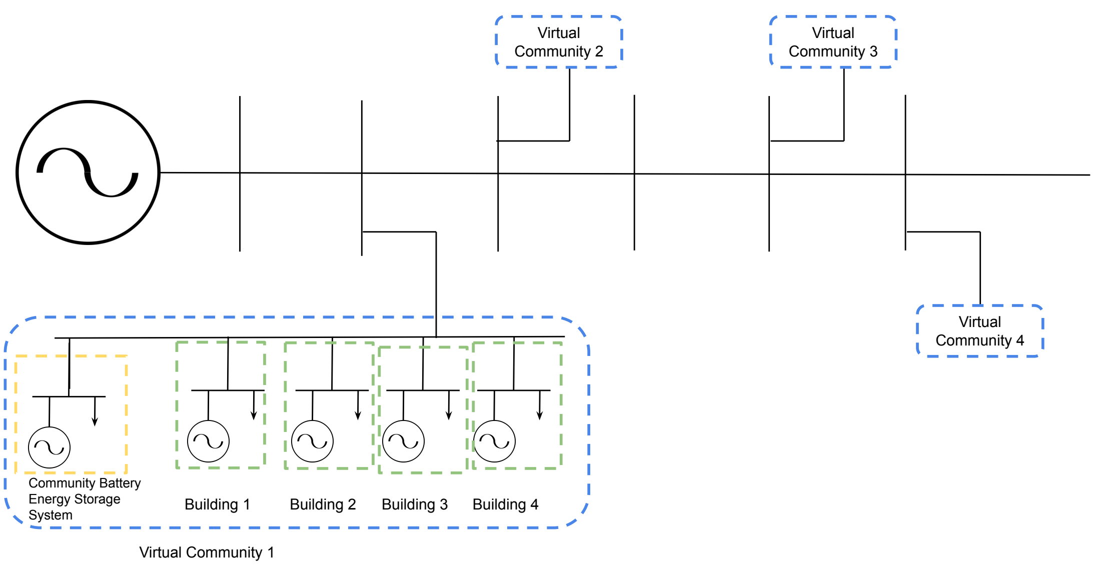

Figure 17: Electrical network analogy

Each building in the B2B energy trading framework can be considered as a node in the equivalent circuit. This is because

- Each building has its own load, renewable energy generation (SPV and WPG), and potentially a battery energy storage system (BESS), making it a distinct entity in terms of power flow.
- The interaction between buildings (energy exchange) can be represented as power flows between nodes in an electrical network.

The buildings are further aggregated into communities, as shown in the figure, resulting in building-to-community(B2C) interactions. The community battery energy storage system (CBESS) acts as an additional node that interacts with all buildings through the community. The buildings interact with buildings of other communities though C2C interactions. Thus, with the help of P2P energy trading at various stages (B2B, B2C, C2C), the cost of all the participants and grid dependency decreases. This equivalent circuit representation effectively models the P2P energy trading framework, with each building considered as a node. This abstraction highlights the interactions among communities, buildings and their shared resources (CBESS), enabling detailed analysis of power flows and cost optimization. The candidate appreciates this opportunity to clarify and enhance the understanding of the proposed framework. This description and figure have been added to the thesis in chapter 4 in section 4.4.

> **14**: **Q4_6**: Figs 4.5 to 4.8 results on building to utility power exchange is good. Some values are-ve. **Is** this energy exchange bidirectional? If so, **where** are the **energy prices** and **energy blocks** during exchange?

Response: The candidate is appreciative of the examiner's question. Yes, the energy exchange in Figures. 4.5 to 4.8 is bidirectional, meaning buildings and communities can both buy and sell energy depending on their surplus or deficit. Negative values indicate energy export (selling), while positive values represent energy import (buying).

The energy prices for different exchanges (Community-to-Utility, Community-to-Community, Building-to-Building, and Building-to-Community) are already determined in the pricing mechanism discussed in the thesis through Figure 4.9 and 4.10 (in the thesis). These include C2C, B2B, and B2C prices, which govern the cost of energy transfer at each level. The energy blocks or the amount of energy traded are defined in the optimization framework and vary dynamically based on the demand and supply conditions of the participants. These values are explicitly provided in the results and figures illustrating the energy flow among entities as can be seen from Figures 4.5 to 4.8 (in the thesis). The candidate hopes this explanation clarifies the examiner's query.

Chapter-5: Network-Constrained P2P Energy Sharing through Virtual Communities

> **1**: This chapter describes the Virtual Community for Peer to Peer Energy Sharing

Response: The candidate expresses her gratitude for the examiner's keen observance.

> **2**: **Q5_1:** Figs 5.1 and 4.1 appear to be similar. **Are** chapters 4 and 5 similar also?

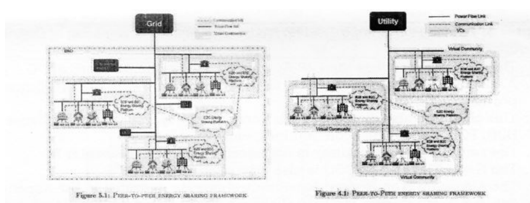

Figure 18: Given by examiner for comment 2

Response: The candidate is grateful to the examiner for this question. Yes, Figure 5.1 and 4.1 appears to be similar. However the difference is present due to the presence of the DSO (distribution system operator) in Figure 5.1 as compared to Figure 4.1.

Table 11: The difference in Chapter 4 and Chapter 5

Concepts	**Chapter 4**	**Chapter 5**
Peer-to-Peer Energy Trading	✓	✓
Multi-community	✓	✓
Renewable Uncertainty	×	✓
Game involved	Non-Cooperative Game	Cooperative Game (Nash Bargaining)
Network Contraints	×	✓

As can be seen from Table 11, the chapter 4 and 5 are not similar, as they address different aspects of P2P energy trading with distinct methodologies and considerations.

Chapter 4 focuses on a non-cooperative game-theoretic approach for P2P energy trading without considering network constraints. Here, buildings and communities optimize their energy exchange strategies independently, aiming to maximize individual benefits. Pricing mechanisms such as C2C, B2B, and B2C prices are determined based on decentralized decision-making.

Chapter 5, on the other hand, integrates network constraints by incorporating the Distribution System Operator (DSO), which performs Optimal Power Flow

(OPF) to determine Locational Marginal Prices (LMPs). This chapter also introduces network utilization charges based on LMP and accounts for renewable energy uncertainties, which were not considered in Chapter 4. Additionally, a cooperative game-theoretic approach is used instead of a non-cooperative one, allowing participants to collaborate for improved cost allocation and efficiency.

Thus, while both chapters deal with P2P energy trading, their methodologies, objectives, and constraints are fundamentally different. The candidate hopes this explanation clarifies the examiner's query.

> **3**: **Q5_2: Is** the problem formulation in sec 5.2.2, the same in chapters 4 and 5? Same Game theory is described in sec 5.3.1

Response: The candidate extends her thanks to the examiner for this question. The building-level problem formulation in Section 5.2.2 is indeed the same as in Chapter 4, as both chapters consider the same optimization framework at the individual building level. However, the overall approach and methodology differ significantly.

Chapter 4 employs a non-cooperative game-theoretic approach, where buildings optimize their strategies independently without considering network constraints.

Chapter 5 introduces network constraints through the DSO performing OPF to determine LMP, along with network utilization charges and renewable uncertainties, which were not included in Chapter 4. Additionally, it applies a cooperative game-theoretic approach instead of a non-cooperative one, allowing participants to collaborate for better cost allocation and system efficiency.

Regarding Section 5.3.1, while both chapters discuss game theory, the type of game-theoretic approach used is different. Chapter 4 uses a non-cooperative game, whereas Section 5.3.1 in Chapter 5 discusses a cooperative game, making their applications distinct. The candidate hopes this explanation clarifies the examiner's query.

> **4**: **Q5_3: Is** the work on P2P Energy Exchange or P2P Energy Trading related to Virtual Power Plant (VPP)?

Response: The candidate sincerely thanks the examiner for the comment. The concept of P2P energy exchange/trading is indeed related to a Virtual Power Plant (VPP), particularly through the formation of virtual communities. However, there are key differences in their roles and functionalities.

- In this work, virtual communities act as aggregated entities where buildings share energy among themselves. Unlike a traditional VPP that primarily functions as a virtual generator, a virtual community can sometimes act as a virtual load, depending on the energy availability and demand.

- Both VPPs and virtual communities involve energy management and optimization, and both utilize Battery Energy Storage Systems (BESS) to enhance flexibility and reliability. However, in a VPP, the energy exchange is typically coordinated by a central operator, while in a P2P framework, decision-making remains more decentralized, allowing prosumers to interact directly.
- Virtual Communities (VCs) in P2P trading share energy among themselves, allowing prosumers within the community to trade energy flexibly. VPPs, on the other hand, do not enable direct energy sharing among participants. Instead, a VPP aggregates the energy resources and optimally dispatches them to the grid as a single entity.

Thus, while virtual communities share some characteristics with VPPs, particularly in energy aggregation and storage, their fundamental difference lies in their operational flexibility—virtual communities can act as both virtual power plants and virtual loads, whereas a VPP primarily functions as a power generator. The candidate hopes this explanation clarifies the examiner's query.

5: Table 5.3 is the same as table 4.5.

Table 5.3: Description of Installed capacity of Solar Power Generation (SPG), Wind Power Generation (WPG) and Battery Energy Storage System (BESS)

	VC1			VC2			VC3		
	B1	B2	B3	B1	B2	B3	B1	B2	B3
SPV (kW)	125	125	125	100	125	125	100	100	100
WPG (kW)	100	100	100	50	100	100	50	50	50
BESS (kW)	200			200			200		

Table 4.5: Installed capacity of Solar Power Generation (SPG), Wind Power Generation (WPG) and Battery Energy Storage System (BESS)

	C1			C2			C3		
	B1	B2	B3	B1	B2	B3	B1	B2	B3
SPV (kW)	125	125	125	100	125	125	100	100	100
WPG (kW)	100	100	100	50	100	100	50	50	50
BESS (kW)	200			200			200		

Figure 19: Given by examiner for comment 5

Response: The candidate expresses her gratitude to the examiner for his observation. Tables 4.5 and 5.3 are identical because they present the same input parameters for the communities and buildings, including solar, wind, and battery energy storage system ratings. This consistency in input data is intentional. While the input parameters remain the same, the overall approach, optimization process, and outcomes in the two chapters are distinct. Chapter 4 focuses on the formation of virtual communities and a decentralized trading mechanism through non-cooperative game, whereas Chapter 5 explores a different framework or strategy for energy transactions including the network constraints. A brief comparison on these two chapters is given Table 12. The candidate expresses her gratitude for the examiner's feedback and remains open to further clarifications.

Table 12: The difference in Chapter 4 and Chapter 5

Concepts	**Chapter 4**	**Chapter 5**
Peer-to-Peer Energy Trading	✓	✓
Multi-community	✓	✓
Renewable Uncertainty	×	✓
Game involved	Non-Cooperative Game	Cooperative Game (Nash Bargaining)
Network Contraints	×	✓

6: **Q5_4**: **Are** the results of chapters 4 and 5 the same?

Response: The candidate is gratefull to the examiner for the comment. The results of Chapters 4 and 5 are not the same due to differences in the game-theoretic approach and network constraints.

Chapter 4 uses a non-cooperative game without network constraints. In this case, each participant optimizes its own strategy independently, leading to a Nash equilibrium, which is not necessarily the optimal solution from a system-wide perspective. Also, due to the lack of network constraints in Chapter 4, the energy exchange is purely based on economic incentives among prosumers.

Chapter 5 applies a cooperative game with network constraints, where participants collaborate to achieve a socially optimal solution. The equilibrium in this case corresponds to an optimal point, ensuring better cost efficiency and power distribution. In Chapter 5, network constraints (e.g., line limits, voltage constraints, Locational Marginal Pricing (LMP)) are incorporated, affecting both power flows and cost allocation.

As a result, there is a slight variation in power and cost results between the two chapters, reflecting the difference between unconstrained decentralized trading (Chapter 4) and constrained, optimized trading (Chapter 5). Thus, while both chapters address P2P energy trading, their methodologies lead to different equilibrium conditions and, consequently, different results. The candidate hopes this explanation clarifies the examiner's query.

7: Fig 5.3 is good as it provides the details of the proposed method.

Response: The candidate wants to thanks the reviewer for this compliment.

8: Fig 5.4 should be shown as a line graph instead of a bar chart.

Response: The candidate sincerely thanks the examiner for this question. The bar graph from Fig.5.4(b) has been modified to line chart as shown in Figure 20.

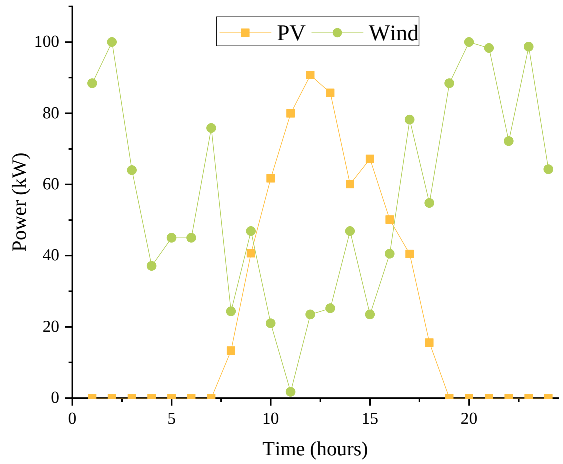

Figure 20: Renewable energy sources (RES) power generation

9: The power exchange in B2C seems to be bidirectional. A detailed description of the exchange is to be provided

Response: The candidate acknowledges the examiner's observation and confirms that Building-to-Community (B2C) energy exchange is indeed bidirectional. In the proposed framework, buildings function as active participants in a decentralized energy network, where they not only consume electricity but also generate, store, and exchange it dynamically. This bidirectional energy exchange is facilitated by multiple mechanisms, ensuring an optimized, efficient, and resilient energy ecosystem. The key mechanisms enabling this B2C exchange include the following.

- Beyond intra-community energy trading, buildings can also exchange energy with buildings in other communities, fostering a larger cooperative energy network. This mechanism balances regional energy demand and supply, reducing transmission losses and increasing overall efficiency. They do the same with the help of community,
- The inclusion of battery storage allows buildings to store excess energy when generation exceeds demand and release it when needed. These storage systems smooth out power fluctuations, reduce dependency on the grid, and enhance energy autonomy. The buildings share a single battery energy storage system (BESS) within a community. Thus, power exchange with BESS also occurs through B2C power exchange.
- Buildings are connected to the main electrical grid through the community itself, allowing them to import power during periods of low local generation

and export surplus energy when they produce more than they consume. This grid interaction provides stability and flexibility, especially when renewable energy production fluctuates. Thus, buildings' energy exchange with the grid also contribute to B2C energy exchange.

By leveraging these mechanisms, the framework promotes energy efficiency, sustainability, and resilience, transforming buildings from passive consumers into dynamic energy hubs. This description has been added in chapter 5 in section 5.3.1.

Chapter-6: Peer-to-Peer Energy Trading Model with Active Participation of Distributed Generation

1: This chapter describes the P2P Energy Trading in the presence of DG.

Response: The candidate acknowledges and values the examiner's observations.

2: A cloud computing framework of P2P, B2B, B2C with Energy Storage is provided in fig. 6.1

Response: The candidate appreciate the examiner's observations.

3: This chapter 6 also discusses with Energy Trading and Energy Exchange with B2B, P2P. B2C, virtual communities, etc.

Response: The candidate sincerely appreciates the examiner's detailed observations.

4: The same virtual community is discussed in 6.2.3 as in chapter 5.

Response: The candidate thanks the examiner for their valuable observations. Virtual communities are formed by aggregating buildings to facilitate energy management and trading. In Chapter 5, these buildings are equipped with renewable generation sources and flexible loads. Additionally, in Chapter 6, HVAC loads are incorporated, adding another layer of complexity to the energy optimization process. While the virtual community structure remains the same, the introduction of HVAC loads in Chapter 6 leads to different energy dynamics and system behavior.

5: The Game Theory and DSO is also discussed in Chapter 5.

Response: The candidate thanks the examiner for their insightful observation. Game theory and the role of the Distribution System Operator (DSO) are indeed discussed in both Chapter 5 and Chapter 6. However, there are key differences in the approach and outcomes.

In Chapter 5, a cooperative game is formulated using the Nash Bargaining model. The DSO maintains the network constraints with the help of DGs who participate on a marginal cost basis. In contrast, Chapter 6 employs the Kalai-Smorodinsky (KS) Bargaining model, which alters the profit distribution dynamics. The DGs in this model are also profitable. The comparison of these two chapters are given in Table 13. The candidate expresses her gratitude for the examiner's feedback and remains open to further discussion on this aspect.

Table 13: Comparison of Chapter 5 and Chapter 6

Concepts	Chapter 5	Chapter 6
Peer-to-Peer Energy Trading	✓	✓
Multi-community	✓	✓
Renewable Uncertainty	✓	✓
Game involved	Cooperative Game (Nash Bargaining)	Cooperative Game (KS Bargaining)
Network Constraints	✓	✓
Active participation of DGs	×	✓
Analysis of effect of participation of DGs actively and marginal cost basis on LMPs	×	✓

6: The Algorithm 5 on Energy Scheduling should be provided in the Appendix.

Response: The candidate acknowledges the examiner's suggestion to include all the algorithms 5 on Energy Scheduling in the appendix with a complete description. However, this algorithm is integral to explaining the step-by-step process of the proposed framework. Placing it within the main chapters ensures clarity in understanding the methodology and its implementation. Moving it to the appendix may disrupt the logical flow of explanation and make it difficult for the reader to follow the problem formulation and solution approach seamlessly. Therefore, the algorithm is retained within the respective chapter to maintain coherence in presenting the research work.

7: Sec 6.3.2 on Market Operation should be provided by means of a block diagram explaining its working.

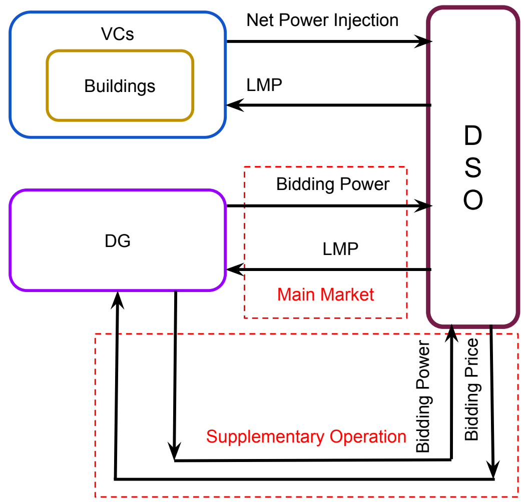

Figure 21: Block diagram for market operation

Response: The candidate sincerely thanks the examiner for their insightful query regarding the block diagram to illustrate the working of Market Operation in Section 6.3.2.

The candidate has added a block diagram as shown in Figure 21. Initially, cloud-based computing in VCs decides the net power injection into the distribution network using decentralised P2P trading, as discussed in Algorithm 5. In parallel to this VC-level optimisation, DGs optimise their objectives for main market bidding by keeping the supplementary operations variables at zero. For clearing the main market, the DSO optimises its problem by considering the net power injection by the VCs and the bid price and power offered by the DGs. If all network constraints are satisfied, the DSO calculates the LMPs based on the dual variables and GSD factors. Otherwise, the DSO performs a supplementary operation to satisfy network constraints. In the supplementary operation loop, the DSO increases the LMPs to the DGs with a fixed step size, and the DGs update their supplementary bidding strategies. This supplementary operation loop repeats until the network constraints are satisfied. This process ends with the satisfaction of the network constraints and the calculation of the corresponding LMPs. Since the cost of resources to make all transactions feasible is captured by the LMPs, all other variables obtained in the supplementary operation are reset to zero. These newly generated LMPs are used for further processing and communicated to all the VCs and DGs for rescheduling. This process is repeated until the difference in LMPs between the subsequent iterations is within tolerance. This description along with the figure has been added in chapter 6 in section 6.3.2.

8: An IEEE 33 bus distribution system is considered in this chapter.

Response: The candidate wants to appreciate the examiner's observation. The modified IEEE 33 bus distribution system is present in the Appendix II of the thesis as can be seen from Figure II.1 (in the thesis).

9: Table 6.3 is similar to table 5.3 and table 4.5, only the location of buses are provided.

Table 6.3: DATA FOR THE BUILDINGS AND VCS USED IN THIS WORK

	C1			C2			C3		
	B1	B2	B3	B1	B2	B3	B1	B2	B3
Rated Load (kW)	125	125	125	100	125	125	100	100	125
PV rating (kW)	125	125	125	100	125	125	100	100	125
WT rating (kW)	100	100	100	50	100	100	50	50	50
BESS rating (kW)	200			200			200		
Bus Location	21			24			18		

Table 5.3: DESCRIPTION OF INSTALLED CAPACITY OF SOLAR POWER GENERATION (SPG), WIND POWER GENERATION (WPG) AND BATTERY ENERGY STORAGE SYSTEM (BESS)

	VC1			VC2			VC3		
	B1	B2	B3	B1	B2	B3	B1	B2	B3
SPV (kW)	125	125	125	100	125	125	100	100	100
WPG (kW)	100	100	100	50	100	100	50	50	50
BESS (kW)	200			200			200		

Table 4.5: INSTALLED CAPACITY OF SOLAR POWER GENERATION (SPG), WIND POWER GENERATION (WPG) AND BATTERY ENERGY STORAGE SYSTEM (BESS)

	C1			C2			C3		
	B1	B2	B3	B1	B2	B3	B1	B2	B3
SPV (kW)	125	125	125	100	125	125	100	100	100
WPG (kW)	100	100	100	50	100	100	50	50	50
BESS (kW)	200			200			200		

Figure 22: Given by examiner for comment 9

Response: The candidate expresses her gratitude to the examiner for his observation. Tables 4.5, 5.3 and 6.3 are identical because they present the same input parameters for the communities and buildings, including solar, wind, and battery energy storage system ratings. This consistency in input data is intentional. While the input parameters remain the same, the overall approach, optimization process, and outcomes in the three chapters are distinct. Chapter 4 focuses on the formation of virtual communities and a decentralized trading mechanism through non-cooperative game, whereas Chapter 5 explores a different framework or strategy for energy transactions including the network constraints with the help of DGs operating on a marginal cost basis. In chapter 5, Nash Bargaining model is used, where as in chapter 6, the cooperative game involved uses KS Bargaining model. The DGs involved in the model of chapter 6 are profitable. A brief comparison on these three chapters is given Table 14. The candidate expresses her gratitude for the examiner's feedback and remains open to further clarifications.

Table 14: Comparison of chapter 4,5 and 6

Concepts	Chapter 4	Chapter 5	Chapter 6
Peer-to-Peer Energy Trading	✓	✓	✓
Multi-community	✓	✓	✓
Renewable Uncertainty	×	✓	✓
Game involved	Non-Cooperative Game	Cooperative Game (Nash Bargaining)	Cooperative Game (KS Bargaining)
Network Constraints	×	✓	✓
Active participation of DGs	×	×	✓
Analysis of effect of participation of DGs actively and marginal cost basis on LMPs	×	×	✓

> **10**: The location of the BESS for IEEE 33 bus network is to be provided as shown below.

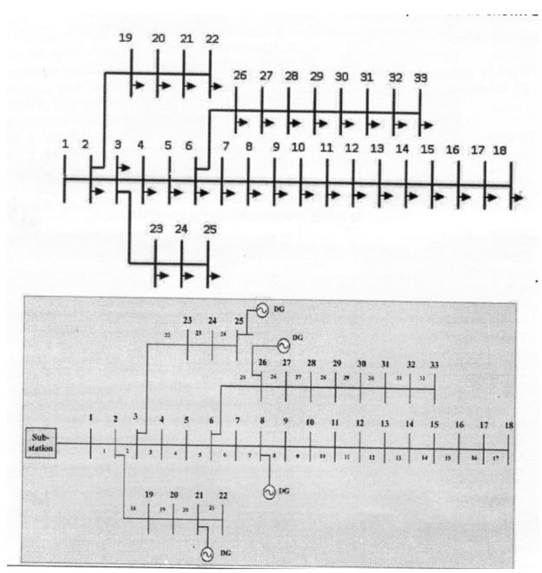

Figure 23: Given by examiner for comment 10

Response: The candidate wants to appreciate the examiner's observation. The modified IEEE 33 bus distribution system is present in the Appendix II of the thesis as can be seen from Figure II.1 (in the thesis).

Chapter-7: Virtual Community based Peer-to-Peer Energy Trading Model including Real Time Scenarios

> **1**: This chapter describes the real time scenario of a virtual community based P2P Energy Trading.

Response: The candidate is grateful for the examiner's insightful observations.

2: **Q7_1: Where** is the **'Real Time Scenario'**

Response: The candidate expresses sincere gratitude to the examiner for this insightful query regarding the real-time scenario in the thesis. In the proposed framework, day-ahead scheduling forms the baseline for real-time operations. The day-ahead schedule is determined based on forecasted data for renewable generation, load demand, and market prices. These schedules optimize energy transactions, including

- Day-ahead schedules calculate building-to-building (B2B), building-to-community (B2C), and community-to-community (C2C) energy exchanges.
- Charging and discharging schedules are optimized to store surplus renewable energy during off-peak hours and discharge it during peak demand periods.
- Adjusting load profiles in response to forecasted demand patterns.
- The schedule determines the quantity of energy imported from or exported to the utility grid.

In real-time operations, these day-ahead schedules act as baseline references but are adjusted dynamically to account for deviations caused by uncertainties in renewable generation or load demand. The real-time adjustments include

- Modifying charging/discharging schedules based on real-time renewable generation and demand fluctuations.
- Balancing discrepancies between scheduled and actual P2P transactions by importing/exporting energy from/to the grid.

Practical Example: Aggregated Profiles of Virtual Community 1 To illustrate this integration, the aggregated load, renewable generation, BESS charging/discharging, and grid exchange power profiles for Community 1 are analyzed as shown in Figure24. These graphs depict these profiles over a 24-hour period.

Day-Ahead Scheduling: During periods of high renewable generation (e.g., midday)(Figure 24(b)), surplus energy is stored in the BESS (Figure 24(c)) or traded with other communities/buildings via P2P transactions. During peak demand hours (around 1700 hours as shown in (Figure 24(a))), stored energy is discharged from the BESS to meet local demand or traded with other participants. Grid imports and exports are minimized as shown in Figure 24(d).

Real-Time Adjustments: The P2P (B2B and C2C) power exchanges are made fixed to the day-ahead values. If actual renewable generation (Figure 24(b)) exceeds forecasts, additional surplus energy is either stored in the BESS or exported to the grid. In case of lower-than-expected generation, additional energy is imported either from BESS (Figure 24(c)) or from the grid (Figure 24(d)).

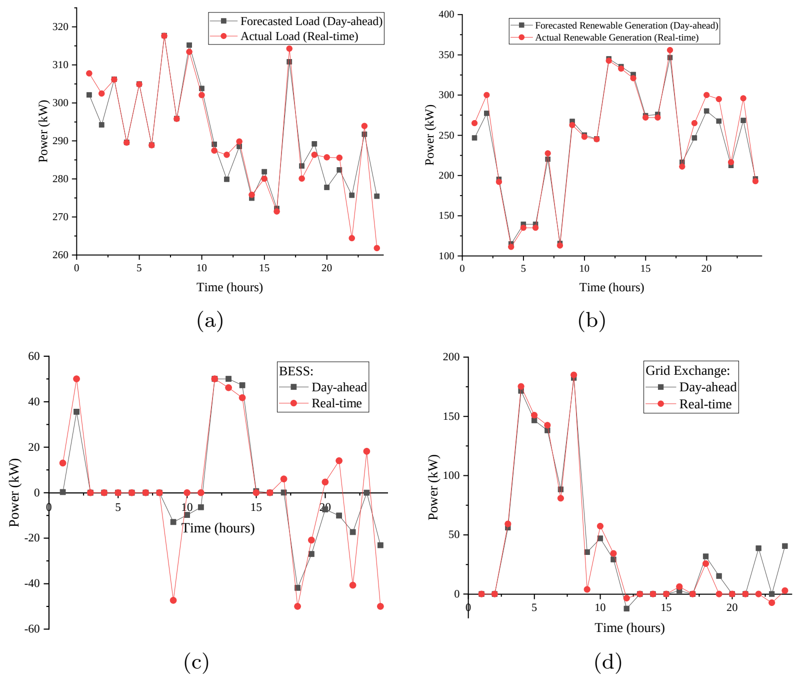

Figure 24: Practical Example: Aggregated Profiles of Virtual Community 1 during day-ahead and real-time operation (a) Load Profile, (b) Renewable generation, (c) BESS charging-discharging power profile, and (d) Grid exchange power profile

The graphs (Figure 24) shows how day-ahead schedules align with forecasted trends while real-time adjustments ensure deviations are managed effectively. This integration ensures that day-ahead schedules provide a baseline while real-time adjustments maintain operational efficiency and reliability of the system. The practical example using virtual community 1's aggregated profiles highlights how this dual-stage approach optimizes energy management in a decentralized P2P trading framework. The candidate appreciates this opportunity to elaborate on this critical aspect of the thesis and believes that this explanation clarifies the integration of day-ahead and real-time scheduling effectively. This description has been added to the thesis in chapter 7 section 7.3.3.

3: This chapter also seems to be similar to earlier chapters 4, 5 and 6.

Response: The candidate understands the examiner's question. The chapter 4,5,6,and 7 have identical layout, but the overall approach, trading mechanism and game theoretical concept involved is different as can be seen from Table 15.

4: Both DSO and Network Constrained operation, are similar as discussed in earlier chapters.

Response:The candidate understands the examiner's question. The chapter

Table 15: Comparison of chapter 4,5,6 and 7

Concepts	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Peer-to-Peer Energy Trading	✓	✓	✓	✓
Multi-community	✓	✓	✓	✓
Renewable Uncertainty	×	✓	✓	✓
Game involved	Non-Cooperative Game	Cooperative Game (Nash Bargaining)	Cooperative Game (KS Bargaining)	Cooperative Game (KS Bargaining)
Network Constraints	×	✓	✓	✓
Active participation of DGs	×	×	✓	✓
Analysis of effect of participation of DGs actively and marginal cost basis on LMPs	×	×	✓	×
Cost analysis of effect of network constraints in Day-ahead scheduling	×	×	×	✓
Real-time load scheduling	×	×	×	✓
Real-time BESS scheduling	×	×	×	✓

4,5,6,and 7 have identical DSO and network constraints, but the overall approach, trading mechanism and game theoretical concept involved is different as can be seen from Table 16.

Table 16: Comparison of chapter 4,5,6 and 7

Concepts	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Peer-to-Peer Energy Trading	✓	✓	✓	✓
Multi-community	✓	✓	✓	✓
Renewable Uncertainty	×	✓	✓	✓
Game involved	Non-Cooperative Game	Cooperative Game (Nash Bargaining)	Cooperative Game (KS Bargaining)	Cooperative Game (KS Bargaining)
Network Constraints	×	✓	✓	✓
Active participation of DGs	×	×	✓	✓
Analysis of effect of participation of DGs actively and marginal cost basis on LMPs	×	×	✓	×
Cost analysis of effect of network constraints in Day-ahead scheduling	×	×	×	✓
Real-time load scheduling	×	×	×	✓
Real-time BESS scheduling	×	×	×	✓

5: The problem formulation in this chapter is good and similar to earlier chapters 4, 5 and 6.

Response: The candidate understands the examiner's question. The chapter 4,5,6,and 7 have identical problem formulation, but the overall approach, trading mechanism and game theoretical concept involved is different as can be seen from Table 17.

6: RTDS was claim to be used as shown in table 7.6

Response: The candidate wants to thank the reviewer for this observation. The work has been validated through a real-time digital simulator (RTDS). The RSCAD model has been given in Appendix II.

7: The image of the RTDS implementation diagram should be provided.

Table 17: Comparison of chapter 4,5,6 and 7

Concepts	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Peer-to-Peer Energy Trading	✓	✓	✓	✓
Multi-community	✓	✓	✓	✓
Renewable Uncertainty	×	✓	✓	✓
Game involved	Non-Cooperative Game	Cooperative Game (Nash Bargaining)	Cooperative Game (KS Bargaining)	Cooperative Game (KS Bargaining)
Network Constraints	×	✓	✓	✓
Active participation of DGs	×	×	✓	✓
Analysis of effect of participation of DGs actively and marginal cost basis on LMPs	×	×	✓	×
Cost analysis of effect of network constraints in Day-ahead scheduling	×	×	×	✓
Real-time load scheduling	×	×	×	✓
Real-time BESS scheduling	×	×	×	✓

Response: The candidate wants to thank the reviewer for this observation.The work has been validated through a real-time digital simulator (RTDS). The RSCAD model has been given in Appendix II. As suggested by the examiner, an image (Figure 25) of RTDS has also been added in the Appendix II.

Figure 25: Image showing RTDS connected to Work Station

Chapter-8: Conclusions and Future Scope

> **1**: This chapter presents important conclusions of the work.

Response: The candidate is grateful for the examiner's observation. The candidate acknowledges that the conclusions chapter should effectively summarize the key findings and contributions of the research. The conclusions have been refined to better highlight the primary outcomes of the work.

> **2**: The summary of each chapter is provided as points.

Response: The candidate understands the importance of summarizing the work concisely and is grateful to the examiner for this feedback.

3: Only Important conclusions are to required be provided as points.

Response: The candidate expresses her gratitude for this suggestion. The conclusions have been revised to emphasize only the critical takeaways from the research. Apart from the chapter vice summary, the important conclusions are also added separately in the thesis.

4: The important contributions from the conclusions and the summary.

Response: The candidate agrees with the examiner's comment. Apart from the chapter vice summary, the important conclusions are also added separately in the thesis.

5: The scholar should write the conclusions to bring out the summary of each chapter.

Response: The candidate has structured the conclusions to cohesively bring out the main findings of each chapter while avoiding a direct restatement of the summaries. The revised section now effectively captures the essence of each contribution.

6: The conclusions should correspond to the objectives identified.

Response: The candidate has ensured that the revised conclusions directly correlate with the objectives stated at the beginning of the thesis. The conclusion section is modified in the thesis as shown below.
The remaining chapters in this thesis address and investigate the P2P energy-sharing framework.

- **Chapter 3:** A probabilistic energy management framework has been proposed to address uncertainties in renewable energy generation, specifically solar and wind energy. The framework utilizes the Nash Bargaining method within a cooperative game setting, incorporating buildings as participants along with a Community Battery Energy Storage System (CBESS). To manage renewable energy fluctuations, Hong's 2m point estimate method has been employed to develop a stochastic energy management model. A comparative analysis of different energy-sharing pricing mechanisms reveals that the incentive method is more efficient due to its reduced execution time, making it preferable for real-time applications. This framework establishes a B2B energy-sharing model within a community of buildings while ensuring computational efficiency.

- **Chapter 4:** A novel decentralized energy management framework has been introduced for virtual communities consisting of buildings equipped with Renewable Energy Sources (RESs) and load-shifting systems. The formation of virtual communities enhances system scalability by reducing the number of transactions and improving computational efficiency. The proposed energy management scheme includes B2B, B2C, and C2C energy trading models while optimizing Battery Energy Storage System (BESS) scheduling and demand-side management. A non-cooperative game-theoretic approach has been implemented in a decentralized manner, allowing participants to act as buyers, sellers, or both, based on their energy needs and availability. The framework ensures secure energy transactions while maintaining grid stability.

- **Chapter 5:** A cost-saving energy management scheme has been developed for virtual communities integrating a shareable BESS. The proposed Locational Marginal Pricing (LMP)-based energy-sharing framework achieves significant cost reductions for all participating buildings while adhering to network constraints. By leveraging the diversity in load patterns across buildings, the scheme enhances the utilization of renewable energy and minimizes reliance on the utility grid. The study demonstrates that, compared to the base case, the proposed framework achieves net cost reductions of 18.3%, 64.9%, and 11.9% in different case scenarios. Furthermore, it effectively manages uncertainties associated with RESs while ensuring optimal energy distribution.

- **Chapter 6:** A P2P energy-sharing framework has been proposed for a distribution system that actively involves Distributed Generators (DGs) and prosumers. The framework enables the Distribution System Operator (DSO) to manage market clearing and supplementary operations with the support of DGs. A cloud-based mechanism is introduced to ensure secure communication, preventing unauthorized data sharing between the DSO and prosumers. The LMP-based energy-sharing model not only reduces energy costs for participating buildings but also enhances the profitability of DGs. The application of the KS bargaining method ensures an equitable distribution of savings among participants while maintaining network constraints. Additionally, the integration of shareable BESS and strategies to address RES uncertainties improves the system's overall resilience and operational efficiency.

- **Chapter 7:** A cost-saving framework for buildings grouped under Virtual Communities (VCs) has been developed to improve scalability and reduce transaction complexities. By leveraging the load diversity among buildings, the framework effectively minimizes power exchange with the utility while optimizing energy-sharing processes. The model integrates both day-ahead and real-time energy market strategies while ensuring compliance with network constraints. The feasibility and effectiveness of the proposed framework have been validated using Real-Time Digital Simulation (RTDS), demonstrating its practical applicability and benefits.

The important conclusions form these chapters can be summarised as shown below.

- A decentralized P2P energy-sharing framework integrating BESS has been successfully designed and implemented, ensuring privacy and security in energy transactions.
- The concept of virtual communities has been effectively employed to reduce computational complexity and improve the feasibility of large-scale energy-sharing models.
- Game-theoretic methods, including cooperative and non-cooperative game approaches, have been utilized to optimize energy trading, ensuring fair pricing and efficient network constraint handling.
- The proposed LMP-based energy-sharing framework has demonstrated substantial cost savings for buildings while improving renewable energy utilization and minimizing reliance on the utility grid.
- Security and privacy concerns in P2P energy trading have been addressed using cloud-based communication frameworks, ensuring safe interactions between prosumers and the DSO.
- The integration of real-time and day-ahead market mechanisms has further enhanced the adaptability and effectiveness of the proposed framework, making it suitable for large-scale implementation in smart grids.
- The feasibility and effectiveness of the developed models have been validated using RTDS, confirming their practical applicability and contribution to future energy management systems.

This research successfully achieves its objectives by developing a secure and cost-effective P2P energy-sharing framework that integrates BESS and virtual communities. The findings provide a strong foundation for future studies and practical implementations in smart grid energy management.