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Micro-Grid Planning with Aggregator's Role in the Renewable Inclusive Prosumer Market

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Abstract

The paper proposes a model for a micro-grid architecture incorporating the role of aggregators and renewable sources on the prosumer side, working together to optimize configurations and operations. The final model takes the form of a mixed-integer linear programming model. This model is solved using the CPLEX solver via GAMS by having a consistent data set.

Keywords

Optimization, Micro-Grid, Prosumers, Aggregators, Renewable Energy, Analytics

1. Introduction

Despite spending heavily on energy infrastructure, the US is ranked behind in key performance indicators like carbon emissions, and energy mix because of its dependency on conventional sources of energy. The current grid faces several challenges. Carbon management has become one of the major challenges. The utility market is continuously evolving, and the electrical power landscape is transforming at a faster rate than ever. The traditional electrical power grid management is characterized by one-directional power flows from producers to consumers. The current electric power landscape is moving towards greater decentralization and multidirectional flows, characterized by greater volatility. Nowadays, the flow of power has become multi-directional and decentralization is taking place for production units at the grid level. Micro-grid architecture is playing a significant role in meeting the growing changes. Prosumers are getting more freedom and rights in terms of energy use. This paper provides an overview of the micro-grid-aggregator architecture incorporating the role of prosumers. The micro-grids truly reflect the present world's electrical scenario. Electricity is turning into a perishable commodity. "Ralph Masiello" and "Julio Romero Aguero" mentioned the term "Uberization of energy" in the IEEE Power and Energy Magazine "Sharing the ride of Power." With the active role of customers participating directly in energy transactions, they have become more informed, involved, and active. The decentralized electrical utility setup has been complemented by distributed energy resources and by demand response actions on the consumers' end. The micro-grid grid model that we are interested in comprises different entities and the balanced interactions between them. The role of prosumers and aggregators is very important which has been discussed in the following subsections. The agents who are acting as producers, as well as consumers of energy in the multi-directional electrical landscape, are termed prosumers. The next electricity boom belongs to prosumers. The "Euro Parliament think tank" is of the view that there has been a significant rise in the number of prosumers in recent times especially because of the fall in the cost of renewable energy technologies such as solar panels, and wind turbines. It is believed that by the end of this year 2020, there will be more than 20 million prosumers in the United States. They are associated with a decentralized, trans-active electric system with high penetration of Distributed Energy Resources (DERs). We can discuss smart prosumers through various dimensions. In terms of resilience and self-healing, prosumers can automatically detect and respond to actual and emerging transmission and distribution problems; the focus is on prevention. In terms of the quality of energy services, they are more modular and tailored to specific end uses, which can vary in quality. In terms of diversification, prosumers encourage large numbers of distributed generation deployed to complement decentralized storage options, such as electric vehicles, with more focus on access and interconnection to renewables and V2G (Vehicle to the grid) systems. It leads to more efficient wholesale market operations in place with integrated reliability coordinators and minimal transmission congestion and constraints. In a decentralized market, the role of the aggregator is important. An aggregator is a broker that acts on behalf of a group or groups of prosumers. It can collect the power flows from many prosumers in order to sell it back to the electrical power system (or the electric utilities). Typically, an aggregator will set up arrangements with a group of prosumers and seek rate offers from suppliers for these different groups of prosumers ("Maryland Office of People's Counsel"). In short, aggregators act as mediators between the main utility market and prosumers. In our model, we are taking the role of renewable generation into consideration. The prosumers are capable of renewable generation besides the demand response actions. The renewable penetration costs due to the use of Distributed energy sources (DERs) on the demand side and the load reduction costs paied by the aggregators to prosumers for the generated power from the use of DERs as well as for the controlled power using demand response actions constitute a part of our model. These costs through the use of renewable sources on the prosumer side are contracted with the aggregator who is acting as a mediator between the grid and prosumers.

2. Literature on Micro-Grids, Prosumers, and Their Analytical Models

A micro-grid is a decentralized group of electricity sources and loads that normally operates connected to and synchronous with the traditional wide area synchronous grid (micro-grid), but can also disconnect to “island mode”—and function autonomously as physical or economic conditions dictate [1]. A micro-grid can connect and disconnect from the grid to enable it to operate in both connected or island mode. There has been a lot of work done in the modeling and stabilizing of the decentralized grids. In an islanded operation mode, droop control is the basic method for bus voltage stabilization when there is no communication among the sources [2]. The authors discuss the stability enhancement of decentralized inverter control through wireless communications in micro-grids [3]. An overview of the various analytical and black box modeling strategies applied to smart DC micro/nanogrid employing different linear and nonlinear modeling techniques are reviewed describing their capabilities, but also their limitations [4]. In a generalized systematic approach to assessing distribution system reliability with renewable distributed generators and micro-grids, the analytical formulation involves the adequacy calculation of conventional and renewable distributed generators supplying micro-grids by using probabilistic models, and adequacy is computed by means of a new general analytical expression which takes into account load-shedding (user load disconnection) and curtailment (user load reduction) policies [5]. The paper discussed a limiting strategy that proposed to improve fault ride-through capability and moreover, a generalized fault model for droop-controlled and directly voltage-controlled inverter-interfaced distributed energy resources to be used in the protection studies [6]. A comparative admittance-based analysis has been carried out between these two approaches where state-space models and more general analytical models are established to derive the output admittance of droop-controlled converter in DC micro-grids [7]. The work evaluates several stability criteria applied to a micro-grid environment, which comprises distributed generators and loads operating on a droop-control strategy in which stability criteria based on impedance matching at the point of application is proposed that can be used in the grid-tied and islanded cases [8]. An approximate analytical model for reliability evaluation of battery energy storage systems is developed in terms of the diverse scenarios, along with multistate models for wind energy system and diesel generating systems with the objective of minimizing the present values of the costs occurring within the project lifetime, and with the constraints of system operation and reliability [9]. The paper discusses a dynamic model that describes the input-output relation between complex power commands sent to the microgenerator inverters and the voltage measurements across the network that approximate well the behavior of the original nonlinear system [10]. Aggregators are relatively new entities in electricity systems that possess the ability to influence a number of grid-connected units via a suitable communication interface. As an electricity grid participant, the aggregator tracks companies' consumption and transmission system operators' requirements in real-time. A prosumer is someone who both produces and consumes energy—a shift made possible, in part, due to the rise of new connected technologies and the steady increase of more renewable power like solar and wind onto our electric grid. Prosumers are growing in the energy space as more Americans generate their own power from distributed energy resources. The aggregator exploits the active participation of prosumers in order to provide commercial service in the power market in which prosumers interact in a distributed environment during the purchase or sale of electric power [11]. The aggregator optimizes the prosumers' flexibility with the objective of minimizing the net cost of buying and selling energy and secondary reserve in both day-ahead and real-time market stages in which the uncertainties of the renewable generation, consumption, outdoor temperature, prosumers' preferences, and house occupancy are modeled through a set of scenarios [12]. The paper addresses the problem faced by an aggregator of small prosumers where the aggregator exploits the flexibility of prosumers' appliances, in order to reduce its market net costs by taking a case study of thousand small prosumers [13]. The authors propose short-term decision-support models for aggregators that sell electricity to prosumers and buy back surplus electricity where the key element is that the aggregator can control flexible energy units at the prosumers, in which the bidding decision is made in the first stage, and the scheduling in the second [14]. A cluster-based optimization approach is illustrated to support the participation of an aggregator of a larger number of prosumers in the day-ahead energy market [15]. The authors proposed a new hierarchical model of predictive control (MPC) to support an aggregator in the delivery of multiple market products through the real-time control of heterogeneous flexible resources where the hierarchical MPC covers the participation of an aggregator in both energy and secondary reserve markets [16]. The paper discusses an economically profitable way to deploy a residential micro-grid incorporating a residential aggregator between the prosumers and the utility by employing certain rules presented as rule-based aggregator business model [17]. The work proposes a new network-constrained bidding optimization strategy to coordinate the participation of aggregators of prosumers in the day-ahead energy and secondary reserve markets where the network-constrained bidding strategy preserves the data privacy of all agents [18]. A two-stage stochastic optimization model is proposed to support the aggregator in the optimal, robust demand and supply bids that is used to deal with the uncertainty of end-user's behavior, outdoor temperature, electricity demand, and PV generation [19]. The impact of demand response aggregators (DRAs) in a prosumer micro-grid is investigated by developing a robust energy and reserve dispatch model and solving a deterministic mathematical formulation for the operational planning of the grid [20]. A generic demand model is being discussed that captures the aggregated effect of a large population of price-responsive prosumers equipped with small-scale PV-battery systems for market simulation in future grid scenario analysis in the form of a bi-level program in which the upper-level unit commitment problem minimizes the total generation cost, and the lower-level problem maximizes prosumers' aggregate self-consumption [21].

3. Model and Method Decsription

Let us define the nomenclature:

Agg_d: Aggregators,

l_c: Prsoumers,

MG_b: Micro-grid,

p_a: Plant,

A: Set of plants (1…a…A),

B: Set of micro-grids (1…b…B,

C: Set of prosumers (1…c…C),

D: Set of aggregators (1…d…D),

I_a: Production costs of plant p_a per MW,

N_{ab}: Electricity transmission costs between plant p_a and migro grid MG_b (that depends on the voltage level) per MW,

K_{bc}: Distribution costs between MG_b and the prosumers per MW, it depends on the contract of electricity supply signed between the electrical utilities and the prosumer,

L_c: Renewable penetration costs due to the use of Distributed energy sources (DERs) in the prosumer (demand) side per MW,

E_{cd}: Power reduction cost per MW of prosumer l_c contracted with the aggregator Agg_d,

F_{db}: Cost of aggregated power per MW collected by Agg_d and delivered to MG_b,

G_a: Fixed installation cost of the plant p_a per MW,

H_d: Fixed operating cost of the aggregator Agg_d,

P_a: Capacity of the power plant p_a in MW,

R_b: Capacity of the micro-grid MG_b in MW,

Q_d: Capacity of the aggregator Agg_d in MW,

dem_c: Effective consumption of prosumer l_c in MW,

dem_Agg_d: Demand of Agg_d in MW.

Decision Variables:

X_{ab}: Power flow value from plant p_a to MG_b measured in MW,

Y_{bc}: Power flow value from the micro-grid MG_b to the prosumer l_c measured in MW,

V_{cd}: Value of electrical power through renewable penetration of power and demand response actions delivered from prosumer l_c to Agg_d and measured in MW,

S_{db}: Value of aggregated power delivered from Agg_d to MG_b measured in MW,

Z_1: if a plant p_a is operating, 0, otherwise.

$$\text{Minimize } \Sigma_a G_a P_a Z_a + \Sigma_d H_d + \Sigma_a \Sigma_b \left(I_a + N_{ab}\right) X_{ab} + \Sigma_b \Sigma_c K_b Y_{bc} + \Sigma_c \Sigma_d \left(L_c + E_{cd}\right) V_{cd} + \Sigma_d \Sigma_b F_{db} S_{db} \quad (1)$$

The objective function of the optimization problem is to minimize the total costs of the system. The cost function is dependent on various parameters. The installation costs of the plants and the fixed operating costs of the aggregators are denoted by first and second terms respectively. The production and transmission costs of electricity are represented in the third part. The fourth part reflects the electricity distribution costs. The fifth part signifies the renewable penetration costs due to the use of Distributed energy sources (DERs) on the demand side and load reduction costs paied by the aggregators to prosumers for the generated power from the use of DERs as well as for the controlled power using demand response actions respectively. The costs of aggregated power delivered from the aggregator participating in the electricity market to the micro-grids are denoted by the last part.

Subject to the following constraints:

$$\Sigma_b X_{ab} \le P_a Z_a \qquad \forall a \quad (2)$$

$$\Sigma_a X_{ab} + \Sigma_d S_{db} \le R_b \qquad \forall b \quad (3)$$

$$\Sigma_c V_{cd} = \Sigma_b S_{db} \qquad \forall d \quad (4)$$

$$\Sigma_d S_{db} + \Sigma_d X_{ab} = \Sigma_c Y_{bc} \qquad \forall b \quad (5)$$

$$\Sigma_b Y_{bc} \ge dem_c \qquad \forall c \quad (6)$$

$$\Sigma_b Y_{bc} \ge \Sigma_d V_{cd} \qquad \forall c \quad (7)$$

$$\Sigma_b Y_{bc} = dem_c + \Sigma_d V_{cd} \qquad \forall c \quad (8)$$

$$\Sigma_c V_{cd} \le Q_d \qquad \forall d \quad (9)$$

$$\Sigma_c V_{cd} = dem\_Agg_d \qquad \forall d \quad (10)$$

$$Z_a \in 0,1 \qquad \forall a \quad (11)$$

$$X_{ab}, Y_{bc}, V_{cd}, S_{db} \ge 0 \qquad \forall a,b,c,d \quad (12)$$

The second constraint (2) signifies that the electricity delivered from plant p_a to each micro-grid is less than or equal to the capacity power plant. The third constraint shows that the sum of the incoming flows from the power plants and from the aggregators to each micro-grid is less than or equal to the capacity of the micro-grid. The fourth constraint shows the sum of the reduced electrical power delivered from prosumer to aggregator is equal to the power delivered aggregator to the micro-grid. The fifth constraint explains that the incoming flows (from aggregator and power plant) of each micro-grid are equal to the sum of its outgoing flows (to prosumer). The sixth, seventh and eighth constraints talk about the balancing of incoming and outgoing flows for each prosumer. The power delivered to each prosumer must be greater than or equal to the demand of each prosumer. The sum of power flow from micro-grid to prosumer must be greater than the sum of reduced power from aggregator to prosumer *i.e.* the sum of the forward flows is greater than the sum of the reverse flows. The ninth constraint shows the capacity constraints of each aggregator and the tenth constraint signifies that the demand of each aggregator is satisfied. And finally, the eleventh constraint shows the binary nature of the decision variable Z_a and the last one is the non-negativity constraint of the decision variables.

There are different sets of parameters that are considered for this optimization model. The first set of parameters is the power-plant parameters. In category p_a, p_1 refers to a gas, p_2 refers to wind, p_3 refers to another gas type power plant. The fixed installation cost is referred to as G_a that will be different for different power plants. I_a is the production cost per MW in USD. The second set of parameters is the micro-grid parameters MG_b: MG_1 and MG_2 which have their respective capacities as R_b calculated in MW. The third set, N_{ab}, is the transmission cost of electricity from the power plant to the micro-grid whereas, K_{bc} is the distribution cost from the micro-grid to prosumer. The fifth set of parameters is the aggregator parameters Agg_d: Agg_1 and Agg_2 whose operating costs are calculated in terms of H_d in USD, demand is calculated in terms of dem_Agg_d in MW and capacity as Q_d in MW. Then, the prosumer parameters l_c: l_1 and l_2 have the effective consumption defined as dem_c in MW including the renewable penetration costs due to the use of DERs in USD. Finally, the selling price of controlled power from prosumers to aggregators is expressed as E_{cd} and the selling price of aggregated power from aggregators to micro-grids is referred to as F_{db}. There are a total of six case studies considered in the optimization model having different sets of parameters discussed above. The data can be summarized in the form of a tabular structure that shows different key parameters for the micro-grid-aggregator model. Six case studies are shown and compiled in one table named Table 1. These contain power plant parameters used for three power plants (p_1(Gas), p_2(Wind), p_3(Gas)), micro-grid parameters for two micro-grids (MG_1, MG_2), aggregator parameters for two aggregators (Agg_1, Agg_2) besides transmission costs, distribution, selling, and other cost parameters.

4. Numerical Results

Table 1 shows the case studies with powerplant parameters, micro-grid, and aggregator parameters. The final model took the form of a mixed-integer linear programming (MIP) model. The model was solved using the CPLEX solver via GAMS. The MIP value for the first case study obtained was USD 404,761,960 with production and fixed installation costs being less for gas power plants in comparison to wind power plants. The two micro-grids have a fixed capacity of 3000 MW. The transmission cost of electricity from the Power Plant to the Micro-grid is USD 40 high terminal block (HTB) line. The demand for the two aggregators is 200 MW and 300 MW whereas the capacity of the aggregators is 1000 MW. In the second case study, the fixed installation costs have been reduced from 2.2 to 5 percent including the production costs. With the induction of

Table 1. Different sets of parameters corresponding to micro-grid and aggregator model in the renewable inclusive market.

Data sets	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case study 6
P_1 (MW)	435	470	370	510	570	295
P_2 (MW)	52	70	700	300	40	40
P_3 (MW)	480	427	560	425	320	380
G_1 (USD)	442,000	432,276	378,000	410,000	600,000	210,000
G_2 (USD)	1,300,000	1,235,000	200,000	970,000	1,050,000	1,070,000
G_3 (USD)	442,000	432,276	400,000	320,000	510,000	270,000
I_1 (USD/MW)	27	24	20	24	40	17
I_2 (USD/MW)	82	79	17	40	62	42
I_3 (USD/MW)	27	24	24	20	37	21
$Mg_1 - R_b$ (MW)	3000	3000	5000	2000	6000	1500
$Mg_2 - R_b$ (MW)	3000	3000	5000	2000	6000	1500
N_{ab} (USD)	40	25	40	35	20	25
K_{bc} (USD)	137.2	120	110	90	70	60
$Agg_1 - H_d$ (USD)	5000	3500	4000	7000	7000	3000
$Agg_2 - H_d$ (USD)	15,000	16,150	12,000	18,000	18,000	11,000
dem_Agg_1 (MW)	200	200	700	250	350	400
dem_Agg_2 (MW)	300	300	800	350	650	300
$Agg_1 - Q_d$ (MW)	1000	1000	2000	800	3000	900
$Agg_2 - Q_d$ (MW)	1000	1000	2000	800	3000	900
$l_1 - dem_c$ (MW)	400	400	500	600	450	370
$l_2 - dem_c$ (MW)	400	400	500	600	290	340
$l_1 - Ren.pen.$ (USD/MW)	50	70	50	45	35	34
$l_2 - Ren.pen.$ (USD/MW)	50	30	50	45	35	34
E_{cd} (USD)	50	65	70	40	40	40
F_{db} (USD)	60	75	90	50	50	55

the latest technologies, the capacity of the wind power plant is improved and the value of power through renewable penetration from DERs and aggregated power is also enhanced. The MIP value for the second case study came out to be USD 388,053,822. The third case study signifies the importance of wind power plants with fewer production costs and improved capacity. The capacity of the micro-grids and aggregators are 5000 MW and 2000 MW respectively. The distribution costs were reduced to USD 110 in comparison to the first case study. The MIP objective function value turned out to be USD 280,523,900 with a relative gap of 0.094324. The fourth case study has high production costs and operational costs of aggregators. The selling price of controlled and aggregator powers has lower values than that of a previous case study which gives a MIP value of USD 374,542,040. The fifth case study has lower renewable penetration costs and significantly lower wind capacity which yields the highest objective value. The least MIP value is obtained in the sixth case study having lower operational costs of aggregators, transmission costs from the power plant to the micro-grid, distributions costs, and fixed installation costs. Therefore, with the improvised renewable inclusive prosumer market and aggregator's role, optimized micro-grid planning can be achieved. This depends and will rely heavily on the development of the DERs technologies in the future.

5. Conclusion

Table 2 represents the optimization results for the micro-grid-aggregator model in the summary form. Table 3 corresponds to the optimization results for the first case study. Tables 4-8 reflect the optimization results using CPLEX for the second, third, fourth, fifth, and sixth case studies respectively. Case study 6 represents the lowest cost function value. It is followed by case study 3 whose objective value turned out to be USD 280,523,900. It is followed by the MIP values of case study 4, case study 2, case study 1, and case study 5 in the ascending order. Figure 1 shows the analysis of objective function values for the six case studies. The lowest cost function value of case study 6 is clearly reflected in the figure. We can compare and contrast results by taking different parameters into consideration. One of the parameters taken into consideration is aggregators. Figure 2 reflects the analysis of the MIP values with the capacity of aggregators as the index. The objective function values do depend on the capacity of aggregators but there are other significant parameters too that influence the overall value of the cost function. One other parameter can be the capacity of the micro-grid. Figure 3 shows the analysis of the objective function values with the capacity of micro-grids as the index. The capacity of micro-grids is highlighted in blue whereas the objective function value is highlighted in orange color. Finally, Figure 4 shows the analysis of objective function values for three power plants by taking parameters into consideration such as the average demand of aggregators (MW), the capacity of micro-grids (MW), and the capacity of the plant (MW).

Table 2. Optimization results using CPLEX.

	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case study 6
Obj. function (USD)	404,761,960	388,053,822	280,523,900	374,542,040	505,515,240	207,571,220
X (p_1, MG_1)	435	470	300	510	420	295
X (p_1, MG_2)	0	0	0	0	0	0
X (p_2, MG_1)	0	0	700	265	0	35

Continued

X (p_2, MG_2)	0	0	0	0	0	0
X (p_3, MG_1)	365	330	0	425	320	380
X (p_3, MG_2)	0	0	0	0	0	0
Y (MG_1, C_1)	900	400	2000	1200	1450	1070
Y (MG_1, C_2)	400	900	500	600	290	340
Y (MG_2, C_1)	0	0	0	0	0	0
Y (MG_2, C_2)	0	0	0	0	0	0
V (C_1, Agg_1)	200	0	700	250	350	400
V (C_1, Agg_2)	300	0	800	350	650	300
V (C_2, Agg_1)	0	200	0	0	0	0
V (C_2, Agg_2)	0	300	0	0	0	0
S (Agg_1, MG_1)	200	200	700	250	350	400
S (Agg_1, MG_2)	0	0	0	0	0	0
S (Agg_2, MG_1)	300	300	800	350	650	300
S (Agg_2, MG_2)	0	0	0	0	0	0
Z (p_1)	1	1	1	1	1	1
Z (p_2)	0	0	1	1	0	1
Z (p_3)	1	1	0	1	1	1

Table 3. Optimization results of case study 1 using CPLEX.

Objective function (USD)	404,761,960
X (p_1, MG_1)	435
X (p_1, MG_2)	0
X (p_2, MG_1)	0
X (p_2, MG_2)	0
X (p_3, MG_1)	365
X (p_3, MG_2)	0
Y (MG_1, C_1)	900
Y (MG_1, C_2)	400
Y (MG_2, C_1)	0
Y (MG_2, C_2)	0
V (C_1, Agg_1)	200
V (C_1, Agg_2)	300
V (C_2, Agg_1)	0
V (C_2, Agg_2)	0
S (Agg_1, MG_1)	200
S (Agg_1, MG_2)	0
S (Agg_2, MG_1)	300
S (Agg_2, MG_2)	0
Z (p_1)	1
Z (p_2)	0
Z (p_3)	1

Table 4. Optimization results of case study 2 using CPLEX.

Objective function (USD)	388,053,822
X (p_1, MG_1)	470
X (p_1, MG_2)	0
X (p_2, MG_1)	0
X (p_2, MG_2)	0
X (p_3, MG_1)	330
X (p_3, MG_2)	0
Y (MG_1, C_1)	400
Y (MG_1, C_2)	900
Y (MG_2, C_1)	0
Y (MG_2, C_2)	0
V (C_1, Agg_1)	0
V (C_1, Agg_2)	0
V (C_2, Agg_1)	200
V (C_2, Agg_2)	300
S (Agg_1, MG_1)	200
S (Agg_1, MG_2)	0
S (Agg_2, MG_1)	300
S (Agg_2, MG_2)	0
Z (p_1)	1
Z (p_2)	0
Z (p_3)	1

Table 5. Optimization results of case study 3 using CPLEX.

Objective function (USD)	280,523,900
X (p_1, MG_1)	300
X (p_1, MG_2)	0
X (p_2, MG_1)	700
X (p_2, MG_2)	0
X (p_3, MG_1)	0
X (p_3, MG_2)	0
Y (MG_1, C_1)	2000
Y (MG_1, C_2)	500
Y (MG_2, C_1)	0
Y (MG_2, C_2)	0
V (C_1, Agg_1)	700
V (C_1, Agg_2)	800
V (C_2, Agg_1)	0
V (C_2, Agg_2)	0
S (Agg_1, MG_1)	700
S (Agg_1, MG_2)	0
S (Agg_2, MG_1)	800
S (Agg_2, MG_2)	0
Z (p_1)	1
Z (p_2)	1
Z (p_3)	0

Table 6. Optimization results of case study 4 using CPLEX.

Objective function (USD)	374,542,040
X (p_1, MG_1)	510
X (p_1, MG_2)	0
X (p_2, MG_1)	265
X (p_2, MG_2)	0
X (p_3, MG_1)	425
X (p_3, MG_2)	0
Y (MG_1, C_1)	1200
Y (MG_1, C_2)	600
Y (MG_2, C_1)	0
Y (MG_2, C_2)	0
V (C_1, Agg_1)	250
V (C_1, Agg_2)	350
V (C_2, Agg_1)	0
V (C_2, Agg_2)	0
S (Agg_1, MG_1)	250
S (Agg_1, MG_2)	0
S (Agg_2, MG_1)	350
S (Agg_2, MG_2)	0
Z (p_1)	1
Z (p_2)	1
Z (p_3)	1

Table 7. Optimization results of case study 5 using CPLEX.

Objective function (USD)	505,515,240
X (p_1, MG_1)	420
X (p_1, MG_2)	0
X (p_2, MG_1)	0
X (p_2, MG_2)	0
X (p_3, MG_1)	320
X (p_3, MG_2)	0
Y (MG_1, C_1)	1450
Y (MG_1, C_2)	290
Y (MG_2, C_1)	0
Y (MG_2, C_2)	0
V (C_1, Agg_1)	350
V (C_1, Agg_2)	650
V (C_2, Agg_1)	0
V (C_2, Agg_2)	0
S (Agg_1, MG_1)	350
S (Agg_1, MG_2)	0
S (Agg_2, MG_1)	650
S (Agg_2, MG_2)	0
Z (p_1)	1
Z (p_2)	0
Z (p_3)	1

Table 8. Optimization results of case study 6 using CPLEX.

Objective function (USD)	207,571,220
X (p_1, MG_1)	295
X (p_1, MG_2)	0
X (p_2, MG_1)	35
X (p_2, MG_2)	0
X (p_3, MG_1)	380
X (p_3, MG_2)	0
Y (MG_1, C_1)	1070
Y (MG_1, C_2)	340
Y (MG_2, C_1)	0
Y (MG_2, C_2)	0
V (C_1, Agg_1)	400
V (C_1, Agg_2)	300
V (C_2, Agg_1)	0
V (C_2, Agg_2)	0
S (Agg_1, MG_1)	400
S (Agg_1, MG_2)	0
S (Agg_2, MG_1)	300
S (Agg_2, MG_2)	0
Z (p_1)	1
Z (p_2)	1
Z (p_3)	1

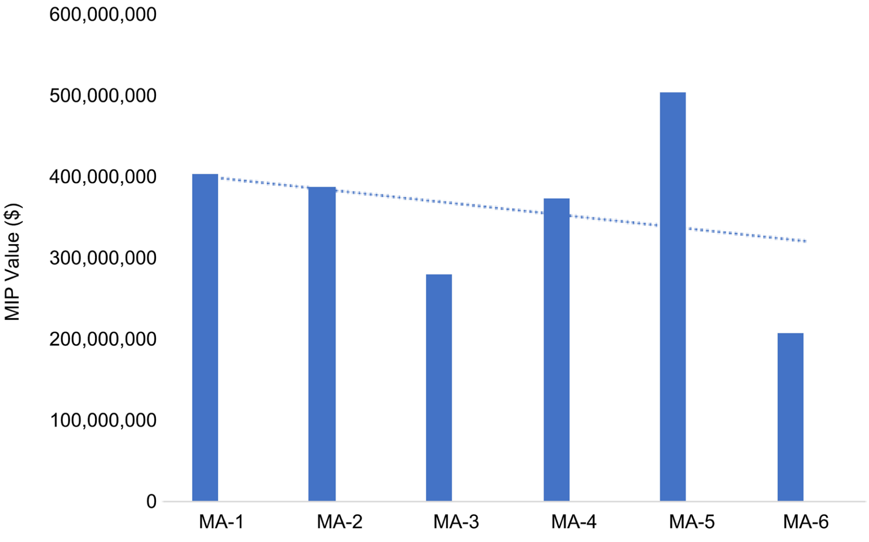

Figure 1. Analysis of objective function values.

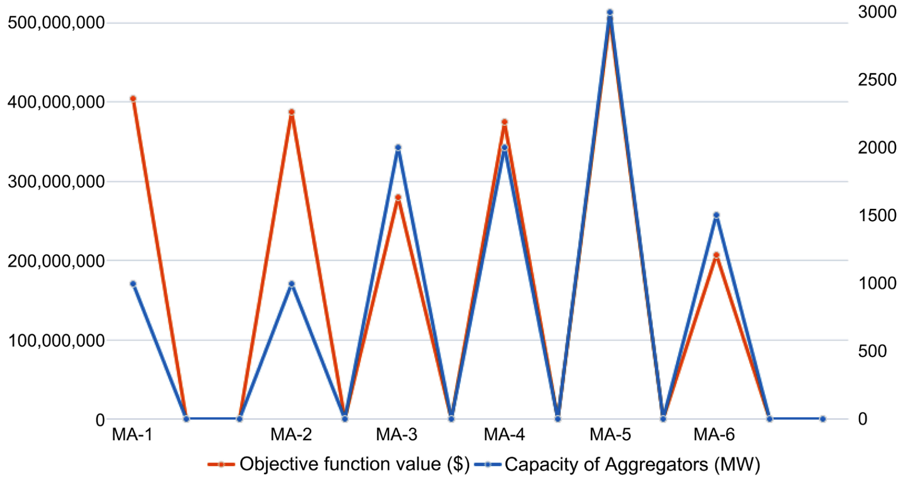

Figure 2. Analysis of MIP values as capacity of aggregators as index.

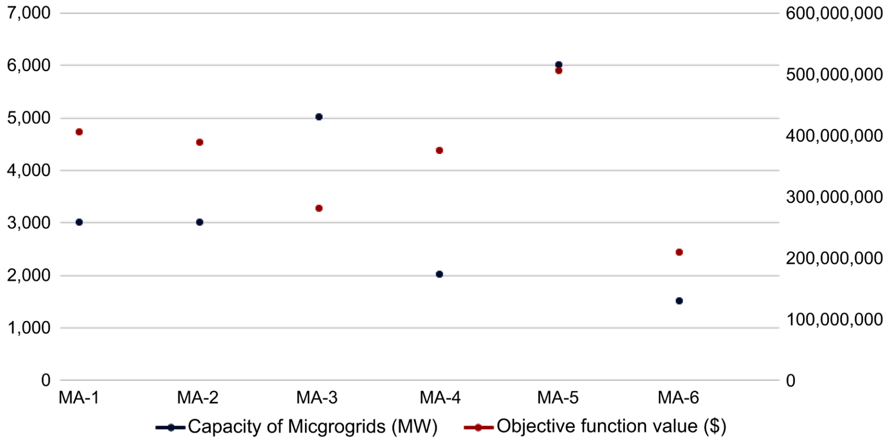

Figure 3. Analysis of MIP values as capacity of micro-grids as index.

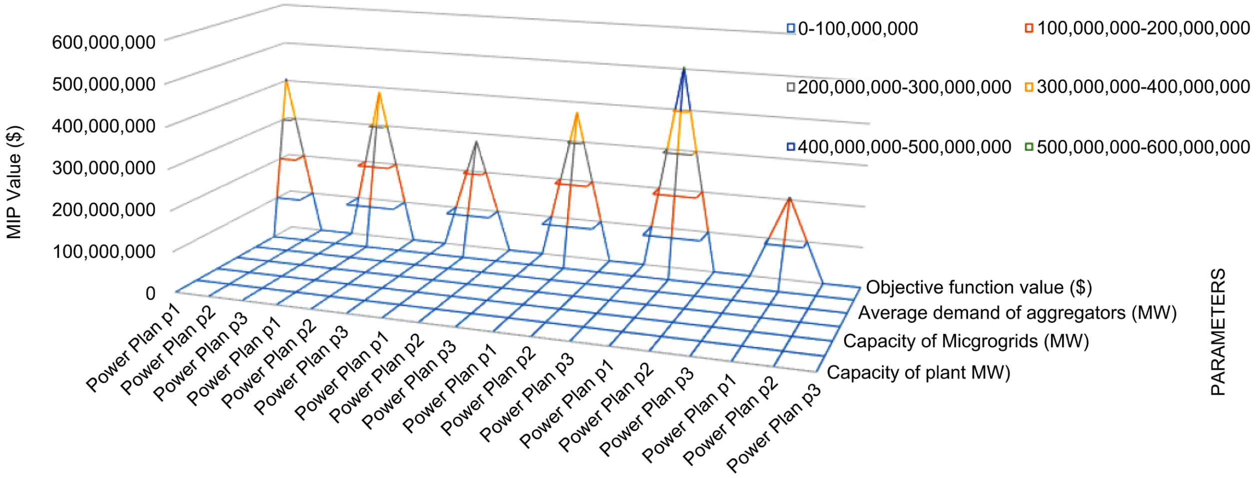

Figure 4. Analysis of objective function values for three power plants.

6. Key Take-Aways and Future Work

This paper presents a model of scenario-based optimal micro-grid aggregator architecture. The model can be used in pushing efforts to decouple the energy sector from carbon emissions. Energy sustainability can be achieved by incorporating the role of the renewable inclusive prosumer market where prosumers can participate more actively. The aggregator role can also play a significant role in optimizing the multi-directional and decentralized energy market. This study can address a number of relevant topics for future research such as the inclusion of more renewable sources in the energy domain economically and the expansion of sustainable energy models.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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