DSO and Aggregator Sharing Concept for Distributed Battery Storage System

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***Abstract*— Increase in electricity demand, mostly due to integration of new technologies electrifying heat and transport, as well as increasing share of distributed generation, create new challenges for distribution system operator (DSO) in terms of reliability and quality of power supply. This is particularly manifested during daily extremes, suggesting there is insufficient capacity of the distribution grid. To avoid expensive and unnecessary investments in new cables and transformers (since events that require network reinforcement are short and rare), the DSO can define a methodology for implementation of so called *non-grid solutions*. This paper analyses a concept in which the DSO signs a contract with the aggregator of flexible resources, offering incentives, such as reduced network fee, for using battery storage when necessary. Since the aggregator is looking for a feasible business case due to high investment cost of storage, the incentives given by the DSO provide a cost-effective investment for the aggregator. The aggregator uses battery storage to minimize the cost of purchasing electricity on the market while the DSO is utilizing it to postpone network reinforcement. The problem is cast as a bilevel problem where the operation of the distribution grid is modelled by *Second-Order-Cone-Programming (SOCP)* relaxation of optimal power flows bidding for the right to use aggregator's battery for preventing violating networks technical constraints. Over a set of scenarios, we demonstrate how coordinated usage of battery storage can postpone network reinforcement while ensuring secure power supply, as well as bring additional cost benefits for the aggregator.**

Keywords—Aggregator, Battery Storage, Distribution System Operator, Reduced Network Fee, Second Order Cone Programming

I. Introduction

Priority of dispatch as well as feed-in tariffs are only a few of the mechanisms encouraging investments in renewable energy sources (RES), however they were the ones impacting the operation and planning of the distribution network, done by Distribution System Operator (DSO), the most. Former passive, or so called fit-and-forget, DSO approach was possible when radial distribution networks were characterized by unidirectional power flow from HV/MV transformer (connecting transmission and distribution network) supplying well-known consumption patterns of end-consumers. This concept was, on the other hand, based on oversizing the network to successfully capture all possible critical scenarios, such as congestion or unacceptable voltage deviation, without monitoring or real-time management. Increasing number of end-consumers with installed PV, during the hours of net-production (when production from PV exceeds consumption) causes reverse power flows and even power flows from distribution to transmission network. Some critical scenarios may congest cables or overhead lines or even the HV/MV transformer, resulting in a need for network reinforcement. Since those critical scenarios are rare and short in duration, investments in new cables and transformers are unprofitable and could increase network losses. DSO faces those challenges through Active Distribution Network Management (ADNM) enabling more efficient network control and operation. On the other hand, as passive end-consumers now become active, an aggregator (or supplier/aggregator) will act on their behalf in the energy market, optimizing the portfolio and achieving the best electricity costs for its users. To increase its flexibility, and potentially profit, the aggregator might decide to invest into battery storage (BS) units and use them to perform arbitrage. Additional opportunities arise from the possibility of "renting" the BS to the DSO and providing a non-grid solution during critical scenarios described above. DSO will create price signals, depending on a number of objectives it can have in distribution network operation and control: power losses minimization [1-4], peak shaving [5-7], voltage control [8-11], maximization of renewable energy sources production [1], [12].

Aggregators participation in the electricity markets as coordinators of different entities is studied widely. The authors in [13] present Stackelberg game used for aggregator market participation and Nash Bargaining Game for optimizing the interaction between the aggregator and active consumers applied in the Belgium Power System. The bilevel model is used for maximizing the aggregators' profit, while minimizing the cost of each active consumer for purchasing energy, considering market-clearing process and resulting prices. The model described in [14] provides supplier participation on three different energy markets through Stackelberg Game. Its active consumers have inflexible loads which cannot be optimized, as well as flexible loads which are used for heating purposes. The results of a bilevel structured optimization model are prices given from the aggregator to consumers, maximizing aggregators profit and minimizing consumers cost of purchased energy. Three different types of prices are compared (dynamic, fixed and Time-of-Use) and the results show that the best solution is dynamic price system calculated for day-ahead, real-time and ex-post market. The paper [15] analyses individual

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usage of battery storage by the system operator (peak load reduction) and supplier (arbitrage) with an additional combined case where system operator's objective function is presented as a constraint in supplier problem. The work in [16] describes mixed linear programming model in which households equipped with solar panels and battery storage want to minimize the cost of energy purchase and provide frequency response and reserve services. The authors in [17] present Italian Transmission System Operator (TSO) coordination with DSO who operates the active distribution network and interaction with the aggregator of distributed sources using advanced Information and Communication Technology (ICT). The aggregator can offer load shedding on the market to avoid 'alarm' state caused by the loss of generating units or outage of lines and substations. The model described in [18] presents potential negative impact of the aggregator, representing thermostatically controlled loads and electric vehicles, on DSO operation. The approach is based on calculating ranges of flexible consumption such that its performance does not violate grid technical constraints.

Unlike the available literature, the model described herein develops a concept cast as a bilevel Mixed Integer *SOCP* model, focusing on the shared role of battery storages in radial distribution network and describes how providing services to multiple distribution networks where providing services for multiple distribution network stakeholders adds to finding a profitable investment case and providing additional value of storage.

II. MODEL DESCRIPTION

A. Distribution network model

DistFlow model is based on the quadratic Kirchhoff Voltage Law (1-2) and the current on the line *mn* is calculated as (3):

$$U_{n,t}^2 = |U_{n,t}|^2 = |U_{m,t} - I_{mn,t} Z_{mn}|^2 \tag{1}$$

$$|U_{n,t}|^2 = |U_{m,t}|^2 - 2(r_{mn} P_{mn,t} + x_{mn} Q_{mn,t}) + \\ + |I_{mn,t}|^2 ({r_{mn}}^2 + {x_{mn}}^2) \tag{2}$$

$$|I_{mn,t}|^2 = \frac{|S_{mn,t}|^2}{|U_{m,t}|^2} \tag{3}$$

Here $U_{n,t}$ and $U_{m,t}$ present voltage of the bus n and m, $I_{mn,t}$ current on the line mn flowing from bus m to n, Z_{mn} impedance of the line mn, r_{mn} resistance, x_{mn} reactance, $P_{mn,t}$ active power and $Q_{mn,t}$ reactive power flowing from bus m to n.

Equations listed above are non-linear and non-convex and thus cannot be solved using commercial solvers. *SOCP* was firstly introduced in [19] and later the exactness of the relaxations for radial grids are shown in [20-24]. *SOCP* relaxations of the problem are presented with (4-5):

$$u_{n,t} = u_{m,t} - 2(r_{mn} P_{mn,t} + x_{mn} Q_{mn,t}) + \\ + i_{mn,t} ({r_{mn}}^2 + {x_{mn}}^2) \tag{4}$$

$$P_{mn,t}^2 + Q_{mn,t}^2 \leq i_{mn,t} u_{m,t} \tag{5}$$

Variables u_n, u_m, i_{mn} present quadratic absolute values of variables U_n, U_m, I_{mn}. The voltage and current are limited with (6-7):

$$0.81 u^{nominal} \leq u_{n,t} \leq 1.21 u^{nominal} \tag{6}$$

$$i_{mn,t} \leq I_{MAX}^2 \tag{7}$$

DSO aims to postpone network reinforcement needed due to increased power consumption in distribution grid and peak load. Critical scenarios could be cable or HV/MV transformers overloads or unacceptable voltage drops.

The active and reactive power balance of load buses are shown in (8) and (9), while equations (10) and (11) present active and reactive power balance of slack bus:

$$load_{m,t}^{active} = \sum_{k \in K} (P_{km,t} - i_{km,t} \cdot r_{km}) - \sum_{n \in N} (P_{mn,t}) \tag{8}$$

$$load_{m,t}^{reactive} = \sum_{k \in K} (Q_{km,t} - i_{km,t} \cdot x_{km}) - \sum_{n \in N} (Q_{mn,t}) \tag{9}$$

$$P_{d,t} + \sum_{n \in N} (P_{mn,t}) = 0 \tag{10}$$

$$Q_{d,t} + \sum_{n \in N} (Q_{mn,t}) = 0 \tag{11}$$

$load_{m,t}^{active}$ and $load_{m,t}^{reactive}$ present active and reactive load at the bus m, $P_{d,t}$ is active power transferred from transmission to distribution network (the power bought at the market for supplying demand in that feeder by supplier/aggregator increased for the energy losses bought by the DSO), $Q_{d,t}$ is reactive power imported from MV network. The required service for voltage regulation is determined in DSO objective function (12) and sent to aggregator's problem as a fixed value:

$$\min \sum_{t \in T} cp_t \cdot provided\ service_t \tag{12}$$

cp_t is the price for charging or discharging battery required for voltage regulation based on market price or combined of reservation and activation price calculated from postponed network reinforcement pricing mechanism (described in Section V).

B. Aggregator model

The aggregator invests in several battery storages along the feeder and exploits their flexibility for arbitrage purposes. Since investment costs into battery storage units are still high, providing additional services to the DSO (e.g. either ancillary services incentives or reduced network fees) would help the aggregator to increase its profit and reduce the investment time. Aggregator's objective function is cost minimization (13) of energy procurement on the market with fixed values of contracted service (battery charging or discharging) providing to DSO:

$$\min \sum_{t \in T} mp_t \cdot P_{d,t} \tag{13}$$

mp_t stands for day-ahead market price of energy in hour t.

The active power-balance of end-consumers with installed battery storage is given with (14) and storage characteristics with (15-20):

$$-load_{m,t}^{active} + discharge_t - charge_t + \sum_{n \in N}(P_{mn,t}) = 0 \quad (14)$$

$$SOC_{m,t} = SOC_{m,t-1} + charge_{m,t} - discharge_{m,t} \quad (15)$$

$$SOC_0 = SOC_{24} = 0 \quad (16)$$

$$SOC_{m,t} \leq SOC^{max} \quad (17)$$

$$0 \leq \ charge_{m,t} \leq P^{max} \cdot x_t^{ch} \quad (18)$$

$$0 \leq \ discharge_{m,t} \leq P^{max} \cdot x_t^{dis} \quad (19)$$

$$x_{m,t}^{ch} + x_{m,t}^{dis} \leq 1 \quad (20)$$

$SOC_{m,t}$ is state of charge of battery storage *m* limited with battery capacity SOC^{max}, while charge and discharge are limited with P^{max}. Equation (16) shows that battery *m* is empty at the begin and end of the day. $x_{m,t}^{ch}$ and $x_{m,t}^{dis}$ are binary variables indicating charging or discharging actions which cannot be simultaneous (20). Figure 1 presents the model describing above equations.

Model shown in (1)-(20) describes the concept of battery units sharing, where the DSO is looking to find optimal bidding scheme which is more feasible that conventional grid solutions (such as new cables and transformers) while the aggregator improves its business case when compared to market services only. Feasibility of this approach is shown trough savings analysis. The proposed model is tested on several case studies, based on realistic 400 V distributions network, reflecting different conditions which might occur in the network.

III. CASE STUDY

The model is tested on a radial low voltage (LV) 400V distribution grid (20 load buses and lines) which is connected with MV network through MV/LV transformer presented in Figure 2. Battery storages are located at the nodes 7,13,15,16 and 20. MV network and MV/LV transformer are modelled as a slack bus. Line parameters (connecting nodes, length, resistance, reactance and maximal rated current) are given in Table I, while cumulative demand profile from the whole feeder and market prices are presented in Figure 3:

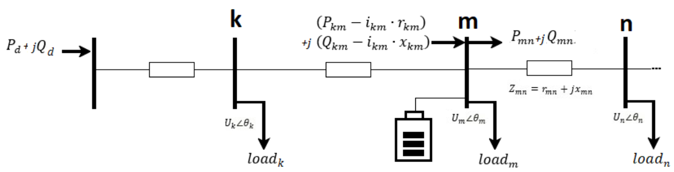

Figure 1 Power flow model

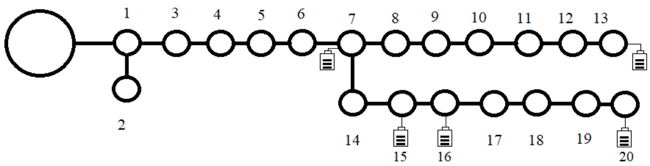

Figure 2 Topology of a single 400 V feeder in analyzed distribution network

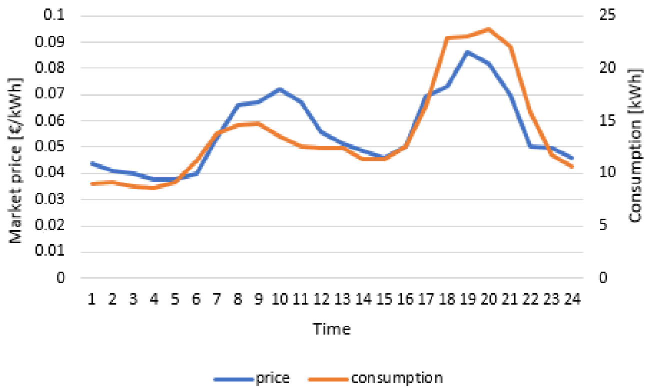

Figure 3 Market prices and cumulative consumption

TABLE I. LINE PARAMETERS

From	*To*	*Length [km]*	*R [Ω/km]*	*X [Ω/km]*	*Imax[A]*
0	1	0.064	0.308	0.281	283
1	2	0.1	0.595	0.302	185
1	3	0.113	0.833	0.313	149
3	4	0.135	0.595	0.302	185
4	5	0.135	0.595	0.302	185
5	6	0.044	0.595	0.302	185
6	7	0.092	0.437	0.302	226
7	8	0.1055	0.437	0.29	226
8	9	0.105	0.437	0.29	226
9	10	0.064	0.308	0.29	283
10	11	0.1545	0.308	0.281	283
11	12	0.0805	0.437	0.281	226
12	13	0.135	0.308	0.281	283
7	14	0.085	0.595	0.302	185
14	15	0.2595	0.833	0.313	149
15	16	0.105	0.437	0.29	226
16	17	0.061	0.308	0.281	283
17	18	0.1545	0.308	0.281	283
18	19	0.0625	0.308	0.281	283
19	20	0.1545	0.308	0.281	283

Several scenarios are analysed:

1. *Case 1*: Initial state of 400 V distribution feeder (before network reinforcement or battery storage);
2. *Case 2*: 400 V distribution feeder considering conventional approach of investing into new cable lines in order to improve the network voltage;
3. *Case 3*: 400V distribution feeder with 5 battery units installed by end-consumers. Energy is procured

through dynamic pricing scheme, while the DSO charges for storage services reflect market prices;

4. *Case 4*: 400 V distribution feeder with 5 battery storages owned by aggregator, providing ancillary services to the DSO and enabling battery usage for end-users with reduced ToU prices;

Each battery storage has 5kWh energy capacity and 0.5 kW charge/discharge power capability. End-consumers are charged for energy according to ToU price scheme with 0.07 €/kWh during the day (8-22h) and 0.09 €/kWh during the night (22-8h), while in reduced ToU with 0.06 €/kWh and 0.0.8€/kWh.

IV. Results

Voltage profile in the case without any network reinforcement or battery storage investment of the critical nodes is shown in Figure 4.

As it can be seen from Figure 4, last six nodes on the feeder have issues as voltage drop is higher than 10% of the nominal value during hours of peak consumption (18^{th} -21^{st} hour). A conventional way of resolving this issue for DSO is cable investment (0.797 km of cable should be reinforced) which costs 31,880 €. Voltage profile with network reinforcement is shown in Figure 5.

An alternative option is to utilize a non-grid solution in form of battery storage and to improve the voltage profile while postponing the network reinforcement. Since these battery units are private property, bought and owned by end-consumers for arbitrage purpose, the DSO should "rent" their flexibility when required. Table II presents consumption decrease required by DSO, while the Figure 6 shows the voltage improvement when the end-consumers provide the flexibility services to the DSO and for arbitrage. As the price of battery storage is falling rapidly [25-26], the calculations are performed with the price of 200 €/kWh, but it should to be noticed that the price is expected to fall below 100$/kWh by 2025. Total investment of each storage system is 1000 €, and if discount rate of 5% and storage life time of 8 years are considered, the net present value of energy storage reduced to annual level is equal to 184.68 €.

The net present value of equipment investment is reduced to the annual level as (21):

$$Investment_{annual} = Investment \cdot \frac{(1+R)^L}{L} \qquad (21)$$

The second factor in (21) reduces the investment to the net present value with the discount rate R during the L period of time (in years) which is equal to the life time of the equipment. Dividing the net present value with expected life time of equipment, net present value is reduced to the annual level.

If end-consumers equipped with battery storages individually procure energy at ToU prices, the investment into storage is not economically feasible only for arbitrage purpose as seen from the Table III comparing the costs listed in second and fourth column. The fourth column presents the annual cost for energy procurement with discounted annual battery investment cost. On the other hand, if end-consumers jointly participate in the market through an aggregator, procure energy at market price and provide flexibility to the DSO, the investment in battery storage is profitable, as seen in Table IV.

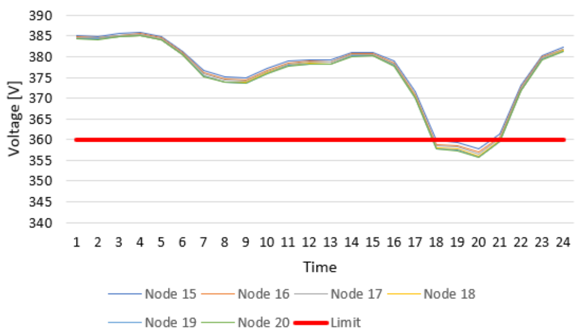

Figure 4 Voltage profile along the feeder

The price for providing services to the DSO is market price multiplied with coefficient 1.5. The value selected for this coefficient could be different, however the authors feel it will not be higher than 1.5, hence giving upper limit of profit.

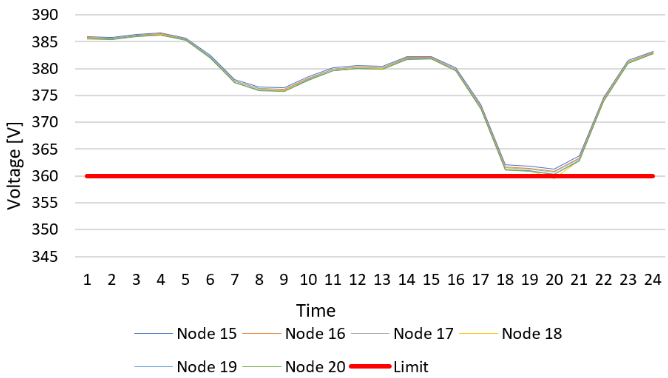

Figure 5 Improved voltage profile with cable reinforcement

TABLE II. REQUESTED FLEXIBILITY IN KW

Consumer	*18 h*	*19 h*	*20 h*	*21 h*
13	-	-	-	-
15	-	-	-0.5	-
16	-0.2703	-0.405	-0.5	-
20	-0.499	-0.499	-0.5	-0.146

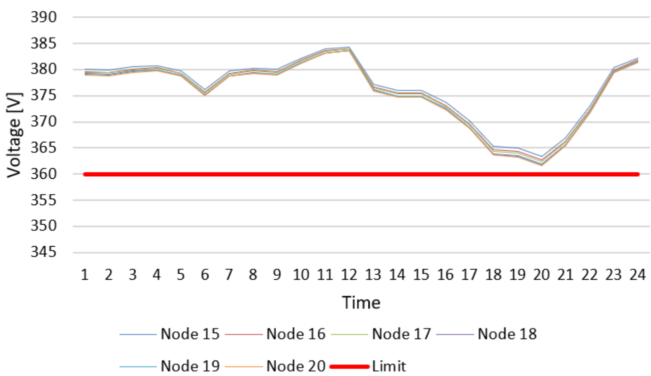

Figure 6 Improved voltage with battery storage activation

TABLE III. ANNUAL COSTS WITH TOU PRICES

Consumer	*Energy cost without battery storage €*	*Energy cost with battery storage €*	*Cost including battery investment €*
7	498.98	469.78	654.46
13	535.25	506.05	690.73
15	661.75	632.55	817.23
16	399.74	370.54	555.22
20	416.94	387.74	572.42

TABLE IV. ANNUAL COSTS WITH DYNAMIC PRICE AND SAVINGS

Consumer	*Cost for energy €*	*Cost with battery investment €*	*Savings €*
7	296.69	481.37	17.32
13	319.39	504.07	31.18
15	385.90	570.58	91.16
16	183.75	368.43	31.31
20	200.01	384.69	32.25

As it can be seen from Table IV, and compared to Table III, annual costs with storage units providing multiple services (including discounted battery investment cost) are lower than energy procurement cost without battery storage. Initial consumption of flexible consumers presented with lines and total battery charging and discharging presented with bars (arbitrage and ancillary services provided to DSO) are shown in Figure 7.

If end-consumers do not invest in battery storage as in private property, aggregator as the individual market participant could gather the group of potentially flexible end-consumers and offer them lower ToU prices to control their flexible consumption through charging and discharging of battery to reduce its energy procurement cost and provide services to the DSO. Costs and savings for consumers involved in demand response program with reduced ToU prices are shown in Table V.

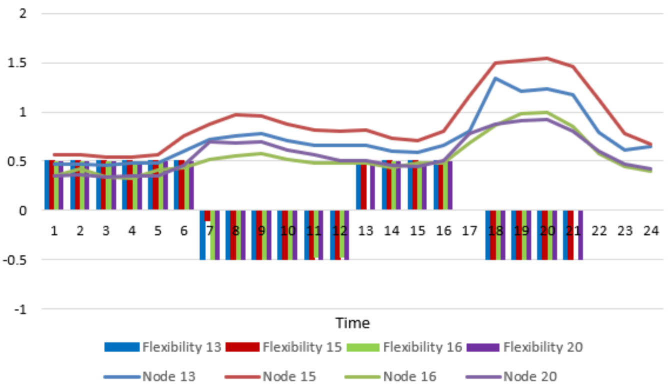

Figure 7 Initial consumption and provided flexibility

TABLE V. ANNUAL COSTS AND SAVINGS WITH REDUCED TOU PRICES

Consumer	*Cost €*	*Savings €*
7	437.52	61.46
13	473.41	61.84
15	585.72	76.03
16	347.48	52.26
20	363.79	53.15

V. FLEXIBILITY PRICES CALCULATION

Pricing mechanism for procuring flexibility from the end-consumers (or aggregator) can be based on market price, as done in previous section or calculated from postponed network reinforcement. Total investment cost in cables is 31,880 €. If an interest rate is 7% [27] and the inflation is 1.3% [28], the maximum price for flexibility for the first year (t=1), if the cable reinforcement is postponed, is calculated as follow (22):

$$Investment_{cost} - Investment_{cost} \cdot \frac{(1+inflation)^t}{(1+interest\ rate)^t} \quad (22)$$

The maximum price for flexibility is 1698.28 €. If the half is used for reservation fee, and the half for activation fee, the reservation price is calculated as (23):

$$Reservation\ price = \frac{Reservation\ fee\ [€]}{Total\ reserved\ capacity\ [kWh]} \quad (23)$$

The activation price is the same as the reservation price if the flexibility price is split in half for each one, but it is paid only if the service is activated.

For services provided as shown in Table II, the reservation price for reserved service (4 kWh each day which result in 1460kWh total over the entire year) is 0.58 €/kWh/activation. It has to be noticed that the DSO pays the reservation for required service for the entire discharging storage capacity. As a simplified way of calculating the income from providing DSO flexibility: consumer 16 has reserved 1.5 kWh capacity and reduces its consumption for 1.1753 kWh totally. Reservation profit is calculated as (24) and the activation as (25):

$$\frac{0.58€}{\mathrm{kWh}} \cdot 1.5\mathrm{kWh} \cdot 365\ \mathrm{reservations} = 317.55\ € \quad (24)$$

$$\frac{\frac{0.58€}{\mathrm{kWh}}}{\mathrm{activation}} \cdot 1.1753\mathrm{kWh} \cdot 365 = 248.81\ € \quad (25)$$

The prices are based on a single-day calculation and more accurate results can be obtained from yearly analysis.

VI. CONCLUSION

Fit and forget approach, which implies that all problems are solved at the planning stage with oversizing the network to ensure secure and quality energy supply, becomes unreasonably expensive since potential network reinforcement could be postponed with integration of battery storages. Ownership of battery storage by the DSO is questionably since they are a regulated system entity, however the end-consumers might decide to invest in batteries to reduce their electricity bill. The investment become profitable by renting and sharing battery capacity with DSO through incentives which are manifested through payments for providing ancillary services to the grid. The contributions presented in the paper are threefold:

- The model determines the required services for voltage regulation from the DSO and compares end-consumers savings through arbitrage only and providing services to the grid with several pricing schemes.
- Model compares conventional approach of new cable upgrade and battery storage integration through voltage improvement and cost savings.
- Two pricing mechanisms are presented and compared for DSO ancillary services favoring one based on postponed network reinforcement.

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