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Author(s): Khajeh, Hosna; Laaksonen, Hannu

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Flexibility Utilization Enabling Business Models and Tariff Structures

Hosna Khajeh, Hannu Laaksonen

School of Technology and Innovations, Flexible Energy Resources, University of Vaasa, Vaasa 65100, Finland

Abstract—**The future distribution network needs more flexibility to deal with the uncertain demand and the increasing number of renewable distributed generations. Although flexible customers located in the distribution network can be used as flexible energy resources, they should be motivated enough so to actively provide flexibility. Local markets and dynamic tariff structures are two methods proposed to incentivize customers. Local markets give distribution system operators (DSO) the opportunity to buy their required flexibility from customers and the customers can make profits by selling their flexibility. Dynamic tariff structures can also monetarily benefit flexible customers if they react to the flexibility requirements. The paper develops these two methods mathematically in a more simple way. It also reviews pricing mechanisms and proposed a tariff design for the DSO that varies according to the location and time. Finally, it implements the tariff design and compares these two methods in the discussion section.**

Keywords—**DSO, distribution network, Dynamic tariff, energy flexibility**

I. INTRODUCTION

The high penetration of renewable distributed generation along with the increasing number of electric vehicles with uncertain charging demand will cause challenges for the operation of future distribution networks. As a result, distribution system operators (DSOs) require more flexibility services from distributed energy resources (DER) to actively control the active and reactive power flows in their network in order to manage congestion and avoid violation of voltage and thermal limits.

One economical solution for congestion management is to utilize the flexibility of the existing resources in distribution networks. However, the existing resources like households need to be motivated enough to react accordingly to the DSO's flexibility needs. Therefore, DSOs seek new business models and strategies that could lead to maximum flexibility deployment in distribution networks.

In this regard, the previous literature's solutions to incentivize customers can be categorized into two approaches. For example, references [1], [2], [3], and [4] proposed that the DSO should purchase flexibility in a local market environment. On the other hand, some works focused on designing different types of tariff structures for DSOs, to operate their networks in real-time and expand them for the future. References [5], [6], and [7] are some examples that tried to adopt the potential flexibility of customers through dynamic tariffs for using distribution networks.

This paper aims to mathematically analyze these two models and compares them together. In this regard, we first propose how the DSO can estimate the required flexibility at each node and each timeslot of the local network. After that, potential pricing mechanisms are reviewed for a local market in which the flexibility is traded. We then proposed a nodal dynamic tariff in which the sensitivity of customer's flexibility and the DSO needs are taken into account. The small case study is also used to calculate the proposed nodal dynamic tariff. Finally, we will compare these two approaches and discuss the advantages of the two approaches.

II. FLEXIBILITY UTILIZATION OF RESOURCES IN DISTRIBUTION NETWORK

In the future, DSOs need to enable business opportunities for smart homes and other flexible distributed energy resources (DERs) to provide flexibility services. The idea behind this motivation is to address local challenges locally [8]. In order to regulate voltages locally and manage congestion within the local network, DSOs require the highest collaborative value of the flexibilities from different flexible resources [9]. In this sense, the location of flexibilities in the distribution network plays a pivotal role to manage the network. For example, the DSO needs decreased consumption or increased production at nodes with a higher voltage level, greater than 1.05 pu, while it requires flexible resources to increase their consumption at nodes with lower voltage levels, i.e. lower than 0.95 pu. Thus, active management of the local network should provide different types of incentives according to the location of the flexible resources and the type of service required by the DSO.

This activity can be associated with the business model concept. To this end, the purchaser or beneficiary of the flexibility is the local DSO whereas the customers are flexible energy resources located in the distribution network. The main value proposition can be defined as efficient and effective operation of the local network and the value creation is the flexible reaction of the customer in response to DSO's flexibility needs.

In this regard, different options have been proposed by the previous literature. The options can be categorized into I) technical solutions, II) tariff or local market-based solutions, III) the utilization of connection agreement and IV) the code/rule-based solutions for the local networks [8], [10]. This paper concentrated on activating the flexibility of smart homes through tariff or market-based solutions.

A. Local market-based solutions

The local market approaches propose that either the DSO or another independent entity organizes a local market in the local network. In the local market, flexibility is traded as a commodity. The flexibility sellers are flexible customers (consumers or/and prosumers) as well as other DERs that can be flexibly scheduled. The buyers are DSOs or other system operators that need flexibility. Reference [11] is an example of a local market in a distribution network. It is a day-ahead local market in which the flexible capacities of prosumers and consumers are traded. If a prosumer sells its flexible capacity at time *t* of the next day, that capacity is reserved and the DSO is able to activate the full or a part of this capacity during time t of the next day. Currently, there exist some pilots in which the DSO utilized local markets for voltage regulations, congestion management or other services in distribution networks [12], [13]. For example, in NODES-project [14] two pilots have been developed to assess if the flexibility markets is effective for solving voltage issues on an island and mainland. Enera introduced by [15], is another project which proposes trading flexibility in the intraday timeframe so that the DSOs can avoid congestion in their local networks.

In spite of the advantages of local markets for trading flexibility, they need costly ICT (Information and Communications Technology) infrastructure as well as smart energy management systems at both customer and DSO ends. First, the independent entity or the DSO, as a local market operator should match the flexibility bids with the flexibility offers and determine the trading prices based on the type of flexible resources and buyers' flexibility needs. This can be a challenging task since each flexible resource has different applications based on their flexibility degrees. For example, batteries can be highly and continuously flexible while relay-based (on-off) appliances are less flexible. In addition, the applications of some appliances, such as thermal controllable appliances (TCL) restrict their flexibility since their first priority is to enhance the thermal comfort of the household customers [16]. Hence, the local market may define a variety of flexible products as flexibility services to fulfil various flexibility needs of the DSO, as proposed by [17].

B. Tariff-based solutions

By 2050, it was estimated that half of all European Union citizens will be equipped with renewable energy resources with a total generation that can fulfil almost 45% of European electricity demand [5]. It is also expected that households are increasingly becoming aware of their energy consumption. Hence, they could be more sensitive to electricity prices and tariffs, especially when they are more and more equipped with home energy management systems (HEMS). As a result, future distribution networks should take advantage of this capability and determine dynamic tariffs. Currently, although there is a possibility for the customers to choose dynamic electricity prices based on spot market prices, they are still subjected to constant tariffs for using the distribution networks. In other words, the distribution network tariff is not a function of the time and location of the customers. DSOs, however, can set dynamic tariffs that reflect the flexibility needs of distribution networks by considering time and location components.

III. REQUIRED FLEXIBILITY

We consider that the DSO uses a piecewise-linearized power flow model to check the voltage and current limits of the network. Simultaneously, it estimates the required flexibility that should be injected/consumed at a specific node. This model has been previously presented in [11]. The following optimization is run for one day (24 hours) on a day-ahead basis. Hence, information about the distribution network tariffs is available on a day before. The main objective of the DSO is to minimize the required flexibility:

$$\min_{P_{n,t}^{up},P_{n,t}^{down}} \sum_t \sum_n P_{n,t}^{up} + P_{n,t}^{down} \tag{1}$$

where, $P_{n,t}^{up}$ is the required upward flexibility at node *n* and time *t* while $P_{n,t}^{down}$ is the downward flexibility needed by the DSO at node *n* and time *t.* Active and reactive power should be balanced at each node and each timeslot, as indicated by (2) and (3):

$$P_{n=PoC,t}^{PoC} - P_{n,t}^{net\ load} + P_{n,t}^{up} - P_{n,t}^{down} - \sum_{n'} \begin{pmatrix} P_{n,n',t}^{pos} - P_{n,n',t}^{neg} \\ +R_{n,n'} SI_{n,n',t} \end{pmatrix} + \sum_{n'} (P_{n',n,t}^{pos} - P_{n',n,t}^{neg}) = 0 \quad \forall n,t \tag{2}$$

$$Q_{n=poC,t}^{PoC} - Q_{n,t}^{net\ load} - \sum_{n'} \begin{pmatrix} Q_{n,n',t}^{pos} - Q_{n,n',t}^{neg} \\ +X_{n,n'} SI_{n,n',t} \end{pmatrix} + \sum_{n'} (Q_{n',n,t}^{pos} - Q_{n',n,t}^{neg}) = 0 \quad \forall n,t \tag{3}$$

Where in (2), $P_{n=PoC,t}^{PoC}\ and\ Q_{n=poC,t}^{PoC}$ are the active and reactive power entering/leaving the local network through the point of coupling (PoC) at node *n* and time *t.* $P_{n,t}^{net\ load}$ and $Q_{n,t}^{net\ load}$ are active and reactive power consumed by customers at node *n* and time *t.* $P_{n,n',t}^{pos}$ and $Q_{n,n',t}^{pos}$ denote the active and reactive power flowing in a downstream direction from node *n* towards node n' whereas $P_{n,n',t}^{neg}$ and $Q_{n,n',t}^{neg}$ are flowing in a upstream direction. $SI_{n,n',t}$ denotes the squared current flowing between *n* and n', and $R_{n,n'}$ and $X_{n,n'}$ are the resistance and reactance of the line.

As (2) states, the flexible power $P_{n,t}^{up}\ and\ P_{n,t}^{down}$ affect the balance constraint and the current and power flowing through the lines. As a result, flexible power of the customers implicitly have an effect on the voltage of each node, as represented by (4):

$$SV_{n,t} - SV_{n',t} - Z_{n,n'}^2 SI_{n,n',t} - 2R_{n,n'} \left(P_{n,n',t}^{pos} - P_{n,n',t}^{neg}\right) - 2X_{n,n'} \left(Q_{n,n',t}^{pos} - Q_{n,n',t}^{neg}\right) = 0 \quad \forall n,n',t \tag{4}$$

Where, $SV_{n,t}$ is the squared voltage at node *n* and time *t.* The squared voltage and squared current are two auxiliary variables that are utilized to linearize the model. $Z_{n,n'}$ indicates the impedance of the line between two nodes n and n'.

It should be highlighted that the flexibility of the customers are highly restricted. This restriction must be taken into account in the power flow model.

In a market-based approach, each customer submits its available flexibility as a flexibility bid at time *t.* Thus, the constraint can be easily written as follows:

$$P^{up}_{n,t} \leq P^{bid,up}_{n,t} \tag{5-a}$$

$$P^{down}_{n,t} \leq P^{bid,down}_{n,t} \tag{6-a}$$

Where, $P^{bid,up}_{n,t}$ and $P^{bid,down}_{n,t}$ are the upward and downward available flexibility bided by customers at node *n* and time *t.* Regarding the downward direction, the customer increases its consumption or decreases its production whereas in the upward direction the customer has the flexibility to decrease it consumption or to increase its production.

In the tariff-based approach, the DSO needs to estimate how much a customer is flexible and sensitive to the tariff prices. In this case, $P^{up}_{n,t}\, and\, P^{down}_{n,t}$ are constrained by the maximum flexibility of the customer at node *n* in the upward direction, $P^{customer,up}_{n}$, and in the downward direction $P^{customer,down}_{n}$. These values can be estimated by the DSO from the historical behavior of the customers.

$$P^{up}_{n,t} \leq P^{customer,up}_{n,t} \tag{5-b}$$

$$P^{down}_{n,t} \leq P^{customer,down}_{n,t} \tag{6-b}$$

The voltage and current should stay between their minimum i.e. v^{min}_{n} , $I^{min}_{n,n'}$ and maximum i.e. v^{max}_{n} and $I^{max}_{n,n'}$ ranges:

$$(v^{min}_{n})^2 \leq SV_{n,t} \leq (v^{max}_{n})^2 \quad \forall n,t \tag{7}$$

$$(I^{min}_{n,n'})^2 \leq SI_{n,n',t} \leq \left(I^{max}_{n,n'}\right)^2 \quad \forall n,n',t \tag{8}$$

The below constraints manage congestion within the line between *n* and n' in which $I^{max}_{n,n'}$ is the maximum current of the line and v^{rated} is the rated voltage equalling 1 pu.

$$P^{pos}_{n,n',t} + P^{neg}_{n,n',t} \leq v^{rated} I^{max}_{n,n'} \quad \forall n,n',t \tag{9}$$

$$Q^{pos}_{n,n',t} + Q^{neg}_{n,n',t} \leq v^{rated} I^{max}_{n,n'} \quad \forall n,n',t \tag{10}$$

Piecewise linearization that has been applied to the power flow constraints are stated in the following [18]:

$$(v^{rated})^2 SI_{n,n',t} = \textstyle\sum_i (2i-1)\Delta S_{\boldsymbol{n,n'}}\, \Delta P_{\boldsymbol{n,n'},i,t} + \sum_i (2i-1)\Delta S_{\boldsymbol{n,n'}} \Delta Q_{\boldsymbol{n,n'},i,t} \quad \forall n,n',t,s \tag{11}$$

$$P^{pos}_{n,n',t} + P^{neg}_{n,n',t} = \textstyle\sum_i \Delta P_{\boldsymbol{n,n'},i,t} \quad \forall n,n',t \tag{12}$$

$$Q^{pos}_{n,n',t} + Q^{neg}_{n,n',t} = \textstyle\sum_i \Delta Q_{\boldsymbol{n,n'},i,t} \quad \forall n,n',t \tag{13}$$

$$0 \leq \Delta P_{\boldsymbol{n,n'},i,t} \leq \Delta S_{\boldsymbol{n,n'}} \quad \forall n,i,n',t \tag{14}$$

$$0 \leq \Delta Q_{\boldsymbol{n,n'},i,t} \leq \Delta S_{\boldsymbol{n,n'}} \quad \forall n,i,n',t \tag{15}$$

$$\Delta S_{\boldsymbol{n,n'}} = \frac{v^{rated} I^{max}_{\boldsymbol{n,n'}}}{P} \quad \forall n,i,n',t \tag{16}$$

Where *i* is the index indicating the partition in the piecewise linearization ranging from 1 to *P. P* is the number of partitions. $\Delta P_{\boldsymbol{n,n'},i,t}$ and $\Delta Q_{\boldsymbol{n,n'},i,t}$ are the discretized active and reactive power flowing between *n* and n' at *t* and $\Delta S_{\boldsymbol{n,n'}}$ is the maximum discretized apparent power flowing within the line between *n* and n'.

The last constraint specify the positive active and reactive power:

$$P^{up}_{n,t}, P^{down}_{n,t}, P^{pos}_{n,n',t}, P^{neg}_{n,n',t}, Q^{pos}_{n,n',t}, Q^{neg}_{n,n',t}, \Delta P_{\boldsymbol{n,n'},i,t}, \Delta Q_{\boldsymbol{n,n'},i,t} \geq 0 \tag{17}$$

By solving the optimization problem (1)-(17), DSO estimates the required flexibility in each direction and determine the flexibility prices according to its needs.

A. Flexiblity prices in local markets

Local market can adopt either pay-as-bid or uniform pricing mechanism to determine the price of flexibility. Reference [11] proposed that in the third stage, the local market tries to match flexibility bids with the flexibility offers of the DSO, using the pay-as-mechanism. It means that the customer receives the payment according to its bided price. The objective of the third stage was to maximize the social welfare of the local market, including the utility of DSO's flexibility demand minus the cost of flexibility sellers:

$$\textstyle\sum_t \sum_n [\pi^{up}_{n,t} P^{up}_{n,t} + \pi^{down}_{n,t} P^{down}_{n,t}] - [\pi^{bid,up}_{n,t} P^{bid,up}_{n,t} + \pi^{bid,down}_{n,t} P^{bid,down}_{n,t}] \tag{18}$$

Where $\pi^{up}_{n,t}$ and $\pi^{down}_{n,t}$ are the upward and downward prices offered by the DSO and $\pi^{bid,up}_{n,t}$ and $\pi^{bid,down}_{n,t}$ are the prices of bids submitted by flexibility sellers, i.e. customers. The following constraints match the sellers' flexibility with the DSO's flexibility needs:

$$P^{bid,up}_{n,t} = P^{up}_{n,t} \tag{19}$$

$$P^{bid,down}_{n,t} = P^{down}_{n,t} \tag{20}$$

In comparison, flexibility sellers can also receive the same local market-clearing price called the uniform price. In the uniform pricing mechanism, the same price is applied to the flexibility of customers at one timeslot. The dual variables associated with constraints (19) and (20) determine the uniform prices.

B. Distribution network dynamic tariffs

The dynamic tariff for the distribution network should have the ability to exploit the maximum flexibility of the customers. We propose that the DSO estimates the sensitivity of the flexible consumption of the customers in terms of price. Then, we define two separate nodal dynamic tariffs to separately activate upward and downward flexibility of customers, as follows:

$$\pi^{tariff,up}_{n,t} = \left(\frac{\partial P^{customer,up}_{n,t}}{\partial \pi^{tariff,up}}\right)^{-1} \quad if\ P^{up}_{n,t} \neq 0 \tag{21}$$

$$\pi_{n,t}^{tariff,down} = \left(\frac{\partial P_{n,t}^{customer,down}}{\partial \pi^{tariff,down}}\right)^{-1} if\ P_{n,t}^{down} \neq 0 \quad (22)$$

$$Cost_{n,t}^{tariff} = P_{n,t}^{net\ load}\pi^{cons} - P_{n,t}^{up}\pi_{n,t}^{tariff,up} - P_{n,t}^{up}\pi_{n,t}^{tariff,down} \quad (23)$$

In (21) and (22), $\frac{\partial P_n^{customer,up}}{\partial \pi^{tariff}}$ and $\frac{\partial P_n^{customer,down}}{\partial \pi^{tariff,down}}$ show how much the upward and downward flexible demand can be activated in terms of distribution network tariffs. If a customer is non-flexible, it only pays based on a constant tariff and its consumption which is equal to $P_{n,t}^{net\ load}\pi^{cons}$. If a customer is flexible, its tariff costs decrease by $P_{n,t}^{up}\pi_{n,t}^{tariff,up}$ when it provides upward flexibility or are reduced by $P_{n,t}^{up}\pi_{n,t}^{tariff,down}$ if it provides downward flexibility. The dynamic tariff should have different values for each node so that only the required flexibility at the specific node is activated.

IV. CASE STUSY AND SIMULATION RESULTS

We consider the same local network as [11]. The LV network studied in the paper is a typical weak Finnish rural overhead network that was extracted and modified from [19]. The local network consists of two LV feeders with ten loading points. Each loading point includes two or three detached houses.

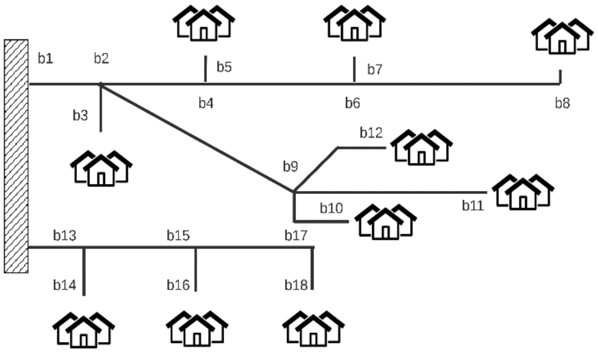

Fig. 1. The local network considered in the paper

We used the hourly net load of detached houses in Vaasa, Finland during the year 2021. Fig. 1 depicts the net loads' mean values for each hour considering one year.

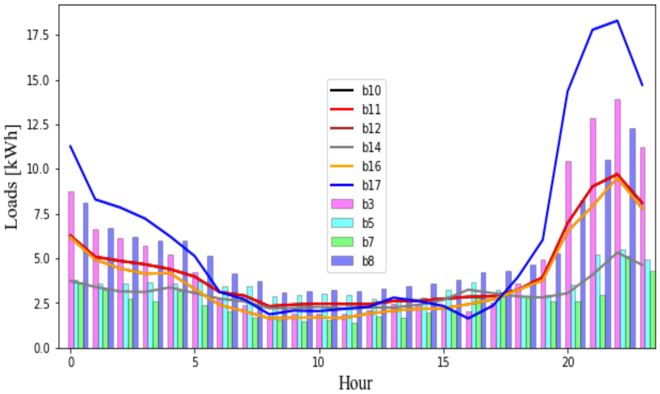

Fig. 2. The net loads' hourly mean values for the houses in 2021, Vaasa

We consider that only 20% of the household consumption can be flexible and sensitive to the distribution tariff. To estimate this sensitivity, linear regression was used and the parameter associated with the price is calculated as the sensitivity of the flexible load to the tariff price. For our case study, this parameter was estimated to be in the range between -0.2 and -0.08 kWh/Cent for the studied household. It means that regarding the historical data, the houses have decreased their consumption when the prices were high. Thus, we conclude that in the future, where the dynamic tariffs are implemented, they will have the same sensitivity to increase or decrease their consumption according to the tariff signals. This assumption could help us to reach a more realistic factor for the value of $\frac{\partial P_n^{customer}}{\partial \pi^{tariff}}$ and therefore to estimate the proposed dynamic tariff.

In the next step, we run the MIP optimization problem (1)-(17) to check the network constraints and to calculate the required flexibility of the local network. One random day was considered in this regard. The results are illustrated in Table I. With the help of the adopted flexibility, the DSO is able to maintain the voltages within the permissible range, as indicated by Fig. 3. Figure 3 illustrates the box plot of the distribution of voltages at different timeslots. Comparing this figure with Fig. 2, the voltage values tend to be lower than 1 pu in situations where the consumption is high. The worst situation for the case study happens at 22, in which the local network requires 1.22 upward flexibility to be able to operate the network in a secure way. This flexibility is adopted from the customer located at node 'b11'. Factor $\frac{\partial P_n^{customer}}{\partial \pi^{tariff}}$ for this customer has been estimated to be 0.12 kWh/Cent. Thus, $Cost_{b11,22}^{tariff,up}$ is equal to 10.16 Cent. It means that the distribution network tariff for the customer located at 'b11' will be reduced by 10.16 Cent, if it provides 1.22 kWh upward flexibility for the distribution grid.

TABLE I. UPWARD AND DOWNWARD FLEXIBILITY REQUIRED BY THE DSO FOR THE CASE STUDY

Timeslot	0-21	22	23
b3	-	-	-
b5	-	-	-
b7	-	-	-
b8	-	-	-
b10	-	-	-
b11	-	1.22 [kW]-upward	-
b12	-	-	-
b14	-	-	-
b16	-	-	-
b17	-	-	-

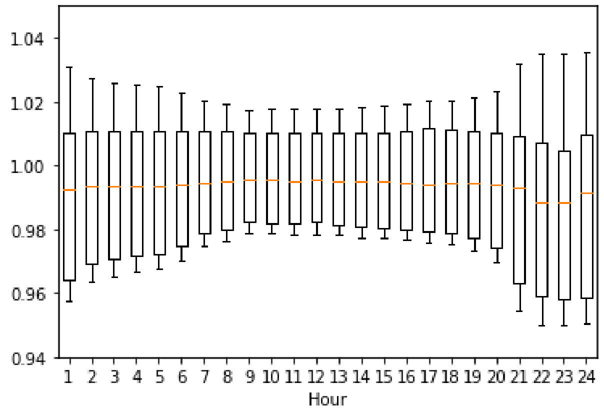

Fig. 2. Box plot indicating the distribution of nodes' voltages in one day

V. DISCUSSIONS AND CONCLUSION

This paper discussed two solutions for a DSO to adopt the flexibility of the local network. One solution is a tariff-based solution in which the DSO was proposed to design flexible distribution network tariffs for flexible customers. In this approach, we proposed that the DSO utilizes nodal dynamic tariffs that reflect its flexibility requirements. This approach aims at specific customer(s) that are located at specific node(s) in required timeslot(s). A case study was also developed for the tariff-based solution.

The other approach was a local market-based approach. This solution requires an active participation of customers in the local market. The DSO purchases the needed flexibility from the customers. Previous literature, such as [17] have tried to develop a competitive local market in which flexibility is traded as a commodity.

Local market-based and tariff-based approaches can be two effective solutions for the DSO to exploit the flexibility in its local network. Each of these approaches has its own advantages and disadvantages compared to the other approach. For example, the market-based solution can have the following benefits:

- The flexibility sellers can directly participate in the local market and submit bids for their available flexibility. As a result, they are responsible for fulfilling their promises and providing the DSO with their flexible capacity if their bids were accepted. However, in the tariff-based approach, the customer may not react to the tariff signal although the DSO has counted on the customer's flexibility. In other words, in the market-based approach, both DSO and customers have more control over their flexibility purchased and sold.
- In the local market, there might be the opportunity for other stakeholders to buy flexibility from the market. Hence, the flexibility sellers may have options to sell their flexibility to other buyers than the local DSO and therefore they could enhance their profits. For example, the flexibility of customers can be sold to transmission system operators (TSO) and balance responsible parties (BRP) besides the local DSO.

On the other hand, the following advantages can be associated with the tariff-based approach:

- It requires less infrastructure compared to the market-based approach. For example, the local market-based approach needs more advanced APIs (Application Programming Interface) to communicate with sellers, buyers, and the market operator. In addition, a market-based approach may require another entity to operate the local market.
- Tariff-based approach might be more simple for the customers as they only receive tariff signals and react accordingly. They do not need to build bidding strategies and follow the market rules.

The DSO can analyze the assets and potential flexibility of the network and plan the best solution based on the available infrastructure and the behavior of the customers in the local network.

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