A toolbox for comparing congestion management solutions for distribution networks

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***Abstract*—To address the emerging challenges in electricity distribution networks, various solutions have been proposed such as alternative tariff design, local flexibility markets (LFMs), bilateral contracts, and local energy markets (LEMs). However, choosing a suitable solution is not straightforward due to multi-dimensional complexity of the challenges which may vary under different circumstances. This paper proposes a toolbox for qualitative and quantitative comparison of the different solutions. The toolbox includes a multi-dimensional analytical framework and a flexible modeling and demonstration platform for conducting quantitative comparison studies. Four solutions i.e. LFM, LEM, cost-reflective tariffs, and bilateral contracts are compared qualitatively using the framework and a real demonstration example of an LFM design is presented utilizing the modeling platform. The toolbox can facilitate research on the local grid challenges and contribute to finding a suitable solution from a multi-dimensional perspective.**

***Index Terms*—Local flexibility markets, local energy markets, distribution network, congestion management, tariff design**

I. INTRODUCTION

Power systems are undergoing a transformation with larger shares of variable renewable energy and electrification in transport, heating, and industrial sectors. The growing volume of distributed generation, increasing electrification, and more variable electricity flows bring challenges to the system which cannot be addressed within the existing market framework. The risk of grid congestion at distribution level becomes higher when more EVs, heat pumps, and PVs are connected. These risks are not currently considered in a framework where markets' bidding zones only intended to handle transmission level bottlenecks. Meanwhile, the distributed energy assets are becoming important resources to deliver renewable production locally, provide flexibility and to balance the system. The true cost or benefit of production or consumption within a network varies over a more granular geographical area but is not commonly reflected in the current market price or grid tariffs [1]. As a result, there are issues regarding accessing flexibility and incentivizing investment at locations with the largest benefits to the system. Moreover, different energy carriers such as heat and electricity are currently traded separately. With the rapid electrification in transport and heating/cooling sector, there are potentials to increase the interaction between different energy carriers. However, measures to facilitate synergies between sectors and enable a more efficient use of available energy resources are lacking [2].

Different solutions have been proposed to address these challenges. Alternative tariff design [3], bilateral contracts [4] and local flexibility market (LFM) [5] have been investigated for distribution system operators (DSOs) to access the flexibility of distributed resources for congestion management. Local energy market (LEM) [6] have also been introduced to improve the energy and economic efficiency at a local level. Some studies [7] compare the various designs respectively for tariff, LFM, etc. However, due to the complexity of the challenges which may vary under different conditions, it is not straightforward to determine the most suitable solution in a specific circumstance while the success potential of a solution highly depends on context. Thus, a holistic approach is needed to assess the effects and feasibility of different solutions.

This paper proposes a toolbox to support a systematic comparison of different solutions for solving the local system challenges. The toolbox consists of two parts: 1) a qualitative analytical framework to identify the barriers of implementing different solutions; 2) a scalable and extendable modeling platform to quantitatively assess their effects under the same system condition. The paper is structured as follows: Section II summarizes four solutions for solving the local system challenges. Section III presents the proposed comparison toolbox. Section IV demonstrates an application of the toolbox: a qualitative comparison of the four solutions in regulatory, technical, cultural and complexity aspects; and implementation of the market-based solution in FlexiGrid project with the modeling platform. Finally, Section V concludes the paper and discusses possible future work.

II. SOLUTIONS TO SOLVE LOCAL SYSTEM CHALLENGES

This section summarizes four typical solutions to address the local system challenges as a replacement for grid reinforcement:

LEM: A local energy market handles energy trading and balance in a local system. The market can either be centralized or decentralized depending on the market clearing. Study [8] presents decentralized market designs with peer-to-peer (P2P) trading. A motivation to engage in P2P trading is that directly trading energy with other prosumers or consumers

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within the community could be more profitable than trading with the DSO or retailers. As a consequence, decentralized trading facilitates utilization of local flexibility and improves self-consumption within the community. However, due to a lack of global perspective of the local system, it is difficult to ensure that the grid limits are not violated. Such drawback can be overcome by centralized market designs such as the one introduced in study [9]. The proposed designs are based on double-side auctions and centralized clearing to maximize social welfare. They resemble the electricity market on transmission level in many aspects while considering the local network constraints. Some market designs [10] [11] also address sector coupling between electricity, heat or hydrogen, to facilitate synergies among different energy carriers in a specific area. LEMs can apply different pricing schemes such as locational marginal pricing or pay-as-bid to reflect the cost for production and consumption.

LFM: A local flexibility market is a market-based approach for DSOs to procure flexibility services. Report [12] summarizes different LFM practices in six European countries. Most flexibility markets are targeted at alleviating capacity issues in regional or transmission grids. Two main lines of thinking for flexibility products are baseline-based and capacity-limit-based products [13]. Unlike LEMs which have multiple buyers and sellers, the major buyer on LFMs is the network operator who obtains services from multiple flexibility providers. Flexibility services are compensated with e.g. pay-as-clear, pay-as-bid, or Vickrey-Clarke-Groves mechanisms. In some designs the market is cleared according to merit order for achieving economic efficiency [14]. The evaluation of flexibility resources might also consider other criteria e.g. comparing the cost with alternative solutions such as temporary subscription rights [15] and rule-based RES curtailment [12].

Cost-reflective tariff: Grid tariffs are charged by DSOs to cover the operational and capital costs of the networks. They are also considered as an instrument to trigger implicit demand response and to incentivize more efficient utilization of distribution infrastructures [16]. Different tariff structures have been proposed to indicate the varying marginal cost of utilizing the grid. In time-of-use tariff or critical peak pricing, higher tariff is charged during peak periods. Customers are expected to actively respond to the tariff by reducing consumption in peak periods and consequently alleviate congestion in the grid. But some work also points out that new load peaks could be created if customers respond to the tariff and shift load in a similar way [1]. One way to overcome the drawback is to include capacity-based charge in the tariff design [17]. The capacity-based tariff is charged e.g. on the highest power during a period, which motivates customers to reduce their maximal consumption. Another way to tackle the problem is introducing step-wise tariff i.e. the tariff is dynamic over time and locations according to the load status in the system [1].

Bilateral agreement: DSOs could also access flexibility from connected customers through bilateral agreements. In some agreements, customers receive incentives to allow DSOs to control their load directly for maintaining the safe operation of the grids [18]. The control can be either disconnecting a load completely or reducing the load over a specific period. It could be applied for the entire connection point or on device level e.g. to control a heat pump or EV charger. In some cases, direct load control is a mandatory term of the connection agreements [19]. In a constrained area, more generators or consumers can be allowed to connect with the grid if they permit DSOs to disconnect or reduce the power flow when necessary. In such cases, the customers do not receive compensations for the non-firm connection [20]. On the other hand, indirect load control is usually achieved by providing incentives for customers to reduce consumption by themselves during specific periods [21]. Unlike LFM, the price for such flexibility service is settled directly between DSOs and customers/aggregators instead of determined on a marketplace. Similar bilateral agreements may also apply to generators that can redispatch the production on request [5].

III. Comparison toolbox

A toolbox is proposed to compare the aforementioned solutions considering a broad range of aspects with both qualitative and quantitative assessment.

A. A multi-dimensional analytical framework

Previous literature [22]–[25] has identified different criteria and barriers for DSOs to adopt innovative methods, market design, or access flexibility. In this paper, a framework is constructed based on the criteria and barriers to qualitatively compare the different solutions considering following aspects:

Regulatory – DSOs are heavily regulated and therefore a key aspect of the comparison is the impact of the regulatory and policy framework, including the type of economic regulation, regulatory incentives, rigidity or pace of change, unbundling requirements, roles and responsibilities, and legal arrangements.

Technical – the degree of technical challenges associated with the different solutions vary and can include lack of appropriate digital and physical infrastructures, technological risk, need for innovations, access to data, and security threats.

Cultural – adoption of new technologies and institutional arrangements depend on acceptance within society and the willingness to adapt, change and innovate within network businesses. As a result, the success of new solutions is affected by the culture within businesses, including attitude towards risk, incentive and capacity for innovation, together with customer behavior, customer engagement, public knowledge and skill.

Complexity – an open and easily understood process will be perceived as fair and more accessible. This is an important aspect that must be considered to avoid any potential market manipulation or abuse of a dominant market position.

B. A flexible modeling platform

To quantitatively compare the different solutions, a modeling platform has been developed. The platform utilizes a reusable structure and includes several grid management tools.

1) A reusable structure: To compare the different solutions, a common and reusable platform is needed. LESOOP is this common platform that is implemented in Python using object-oriented programming to promote reusability [26]. However, an object-oriented structure would not necessarily lead to a reusable design. For a reusable design, the hot spots of application area need to be identified and kept flexible [27]. Our application area is the local energy system studies. To conduct such studies, the platform needs to be flexible with respect to test systems configuration, agents' definition and behavior, and solutions for the local challenges. Therefore, the ecosystem of local energy systems is defined by four main domains in the platform. These main domains are:

- **Network domain**: To represent different energy networks such as electricity, district heating, district cooling
- **Agent domain**: To represent the different type of agents such as households, industries, aggregators, and DSOs.
- **DER domain**: To represent the different energy assets such as storage, heat pumps, PVs, and inflexible loads
- **Solutions domain**: To represent the different solutions mentioned in Section II such as LEMs and LFMs.

To keep the platform flexible and reusable in the mentioned domains, guidelines from [26] has been utilized such as defining classes from an abstract level, minimizing the size of each method as much as possible, and encapsulate functions/methods in the form of black-boxes.

Figure 1 presents the overview of the domains and examples of their content as a Unified Modeling Language (UML) diagram. The content of the solution domain can be different depending on the solution and thus it is shown as an empty block. The abstract classes can be seen on the higher levels of hierarchies in each domain. For example, the Agent superclass can have sub-classes such as End-user, System operator, and Aggregator. The End-user class represents the individual end-users that are connected to the grid. It can be inherited by sub-classes such as residential, industrial, and commercial end-users that can have their specific methods and own different DERs. The domains are connected with each other with the aggregation relationship, showing the association between objects. For example, a DSO may own one or multiple networks, each end-user could own one or multiple DERs, while each DER and end-user are connected to a bus.

Such a design makes the platform flexible and reusble for investigating different test systems and conducting different case studies. This can be done by initializing instances of different classes separately depending on the specific need of a study. For example, for comparing agent-based mechanisms such as LFM and LEM, instances of classes from all the domains are needed. The decomposed domain structure of LESOOP allows different solution blocks to be written separately and be replaced while keeping the rest of the domains constant. This provides the possibility of comparing the different solutions. The platform can be used for other purposes as well. For Building Energy Management System (BEMS) study, only instances of the End-user class and the DER sub-classes can be initialized. In the case of a Model Predictive Control or a congestion forecast study, only sub-classes in the Network and DER domains could work.

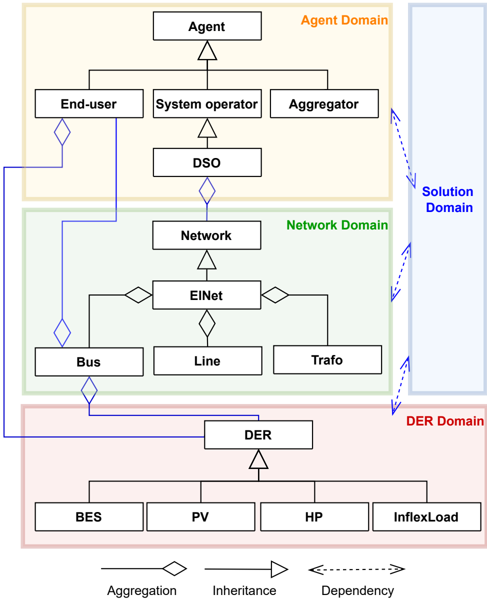

Fig. 1. Overview of the domains and examples of their content in the form of a UML class diagram

2) Decomposition and integration of local grid management tools: Multiple tools are needed to assess the effect of a solution. The quantitative analysis needs e.g. forecasting the production/consumption of DERs, estimating the power flow and congestion risk in grids, and simulating agents' behavior and control logic. These tools are implemented in the platform as class methods. Following the suggestions in [26] for reusability, large methods are decomposed into several methods and are designed to be used as a black-box by the different users of the platform. Therefore, some tools are composed of a group of methods and are written as generic as possible to be independent from a specific application.

The integration of each tool is presented in Table I. As mentioned, the tools are decomposed to increase the reusability. This decomposition is presented in the dependency column of the table. As an example, the DER forecast and scenario generator are independent methods in the DER domain. These tools are used directly in power flow calculator and agent cost optimizer tools, and indirectly utilized in the congestion forecast, agent bidding, and agent dispatch and control tools. Further information on the location and dependency of the tools can be found in Table I.

IV. Utilization of the Toolbox

A. Qualitative comparison of the solutions

The analytical framework proposed in III-A is applied here to identify particular challenges of the solutions introduced in II. Such a comparison indicates the ease of implementation of each solution and its suitability to certain conditions. An overview of the challenges are summarized in Table II.

LEM: Implementing a local energy market is a complex process. Technical infrastructure, such as control systems,

TABLE I
THE INTEGRATION OF DIFFERENT TOOLS IN LESOOP

Required tools	Location in LESOOP	Dependency on other tools
DER forecast	DER domain	-
Scenario generator	DER domain	-
Power flow calculator	Network domain, ElNet class	DER forecaster, and scenario generator
Congestion forecast	Network domain, ElNet class	Power flow calculator
Agents cost optimizer	Agent domain, End-user or Aggregator classes	DER forecaster, scenario generator
Agent bidding	Agent domain	Agent cost optimizer or congestion forecast depending on the agent type
Agent dispatch and control	Agent domain, End-user or Aggregator classes	Agent cost optimizer

metering equipment and user interface, need to be connected to send and receive information. There are regulatory challenges relating to balance responsibility, independence of electricity suppliers and the network operator, and potential market abuse of dominant actors. The complexities of the mechanism may act as a barrier for participation for some actors and could prove politically challenging if the price of electricity is different for end-users within a small geographical area. Moreover, challenges remain related to the interaction between local energy markets and the overlaying energy markets in the current market framework.

LFM: Local flexibility markets may require new and redefined roles and responsibilities on the electricity market, considering restrictions relating to unbundling and balance responsibility. Market monitoring and control must also be considered from both a technical and regulatory point of view to limit the potential for market abuse. Access to the market should be straightforward to allow a large range of participants entry, however, to actively participate in the market, network users need broad knowledge of, among other things, how the market functions, cost and value of flexibility, other participants, and strategy. The information requirement makes local markets complex and is a relatively high barrier for an efficient market with many participants.

Cost-reflective tariffs: Tariffs that accurately reflect network condition require advanced technical solutions for real-time communication that can send signals and receive information instantaneously. However, communicating price signals does not guarantee certain behavior from customers and the exact impact may be difficult to predict and can even have unintended effects. Moreover, if tariffs are to be cost-reflective and proportional to customers' individual network impact, it is unlikely that DSOs are able, due to the price-inelastic nature of electricity demand, to implement tariffs that provide a strong enough incentive for consumers to change their behavior [28]. This is particularly true regarding households, whilst industry is found to be somewhat more responsive [29]. As such, the implicit nature of tariffs may make it difficult for DSOs to rely on for congestion management.

Bilateral contracts: There are no direct technical barriers to bilateral contracts and agreeing bilateral contracts can act as a steppingstone towards a wider market framework, particularly if arranged through an open tendering process. However, this is likely a time-consuming process and engagement with individual service providers requires significant resources, meaning that it is therefore unlikely that smaller actors can enter bilateral contracts without going through an aggregator. This may not be an issue although should be recognized since it would be limiting the options for households and other smaller users to become more active on the electricity market.

B. A real-life demonstration example with LESOOP

In this section, a real-life demonstration of FlexiGrid's LFM [30], [31] on 2022-11-21 is presented as an example for utilizing LESOOP. The demonstration example is on a small area to facilitate the conciseness and readability. For this example, LESOOP's four domains are as follows:

- **Network domain:** The demonstrations are carried out on a section of the Chalmers Campus test-bed [32]. The one-line diagram of the section is presented in Figure 2.
- **Agent domain:** One flexible and two inflexible agents are defined in the demo area (Figure 2 and Table III).
- **DER domain:** The DER assets of the agents are presented Table III. The maximum charging and discharging power for the battery are 95kW and 60kW. The nominal storage capacity is 260kWh. The maximum and minimum state of charge (SoC) are 80% and 20%. The detailed properties of the other DERs are not presented here because the only flexible assets is the battery and the accumulated generation from PVs reaches a maximum of 1.2kW dues to cloud coverage on the demonstration day. Further details about the DERs can be found in [31].
- **Solution domain:** The demonstrated LFM is designed as a double-sided auction with an objective of maximizing the social welfare. DSO is the buyer and flexibility service providers (FSPs) are sellers. The traded product is a capacity-limitation product based on the subscribed capacity of the FSPs. More details on the LFM design can be found in [30], [31].

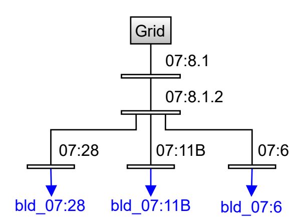

Fig. 2. One-line diagram of the demonstration area

The DSO foresees potential congestions on the line between buses 07:8.1 and 07:8.1.2 based on the congestion forecast results (Figure 3). The congestion forecasts are made utilizing the probabilistic congestion forecast tool in [33]. The presented

TABLE II
THE SUMMARY OF THE QUALITATIVE COMPARISON

	Regulatory	Technical	Cultural	Complexity
LEM	Issues regarding DSO unbundling requirements, market monitoring, and balance responsibility.	Requires advanced technical systems.	Potential equality issues and resistance from DSOs to take on a new role.	Level of automation and data requirement lead to complexities.
LFM	Need new and updated rules and regulatory framework.	Issues regarding baselines and delivery validation besides potential low market liquidity	Potential equality issues due to access to the market and information availability.	Legal and technical complexities can lead to transparency issues.
Tariffs	Alternative tariffs are largely available today.	Requires advanced infrastructure (e.g. IoT enabling and metering)	Potential unintended consequences due to lack of response from users.	Complex to design accurate and reflective network tariffs.
Bilateral contracts	Most parts are allowed within the current regulatory framework.	Limited technical challenges although certain metering and monitoring will be required	Mainly available to large network users, which can be seen as unfair.	Depends on the situation but can be uncomplicated.

TABLE III
AGENTS' LOCATION AND DERS.

Agent id	Bus	Flexible	DERs
bld_07:28	07:28	Yes	3 InflexLoads, 1 BES
bld_07:6	07:6	No	2 InflexLoads, 1 PV
bld_07:11B	07:11B	No	2 InflexLoads, 1 PV

results are based on power flow calculations for 100 scenarios at 19:10 on 2022-11-20 for the coming day. The narrowest and broadest interval spans in Figure 3 include 10% and 90% of the scenarios. Flexible agent bld_07:28 has a subscribed connection capacity of 1000kW. To address the congestion, the DSO and the agents bid in the market day-ahead. Agent bld_07:28 is cleared for capacity-limitation quantities in the range of 579-589kW for the hours 7:00-16:00 when the congestion is forecasted. The agents' cleared quantities on the LFM is the difference between the subscribed connection capacity (i.e., 1000kW) and the imposed cap (See Figure 4).

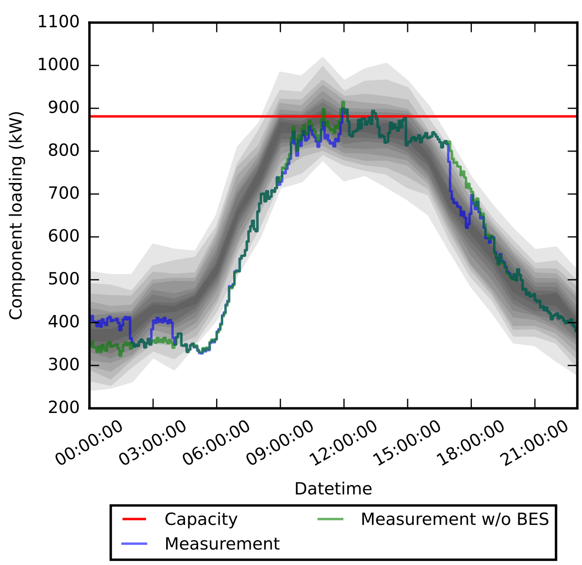

Fig. 3. Predictive interval density plot for congestion forecast and real measurements for the line between buses 07:8.1 and 07:8.1.2 on 2022-11-21

On the delivery day, the agent is dispatching its battery to minimize its cost considering the imposed cap, spot prices, and power tariffs. A distributed dispatch and control is done for each agent. The setpoints are decided every hour for the upcoming hour with a rolling horizon of 24 hours. The details of the dispatch formulation are presented in [31]. The dispatch of agent bld_07:28 is presented in Figure 4. To deliver the sold product, the agent has to keep its imported power (P_{imp}) under the imposed cap. P^{fc}_{imp} is the expected imported power and P^{m}_{imp} shows the measurements. The expected gross load (P^{fc}_{load}) of the agent is expected to be higher than the imposed cap on hours 10 and 11 and therefore the agent adjusts the charge/discharge power P^{fc}_{bes} to reduce P^{fc}_{imp}. The mismatch of the expected and measured P_{imp} are due to the load forecast errors which highlights the importance of stochastic or robust optimization methods to secure the delivery of the service.

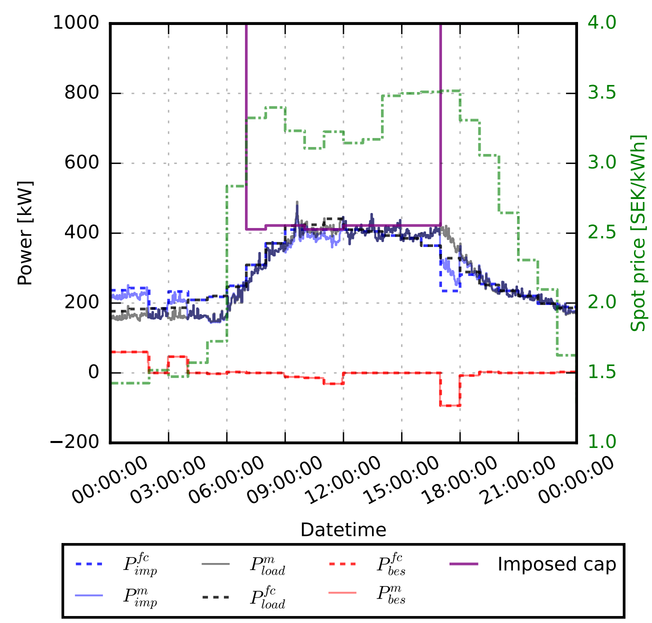

Fig. 4. The dispatch of flexible agent bld_07:28 on 2022-11-21

After the delivery of the product, the impact of the battery dispatch can be seen in Figure 3 by comparing the line loading with and without the battery. The loading have been reduced when considering the battery. However, in some occasions the loading exceeds the nominal capacity. This is due to the forecast errors for different agents. The errors have led to inaccurate battery dispatch for the flexible agent and excessive sell back of the subscribed capacity by the inflexible agents.

V. CONCLUSIONS

This paper proposes a toolbox to compare solutions for tackling the local system challenges. The toolbox includes a multi-dimensional analytical framework and a flexible modeling and demonstration platform for quantitative analysis. Using the framework, four solutions i.e. LFM, LEM, cost-reflective tariffs, and bilateral contracts have been compared qualitatively and a real-life demonstration example for LFM has been presented using the modeling platform. The qualitative results highlight some of the key challenges with the different solutions, e.g. regulations, IoT requirements, and equality issues. The quantitative results emphasize the potential issue with e.g. forecast accuracy. As future work, grid reinforcements can be included in the solutions, the toolbox can be used on a larger area of Chalmers testbed, and more advanced agent's bidding, control and forecasting algorithms can be evaluated. The presented comparison framework and the flexible modeling platform can facilitate research on local energy system studies. It can contribute to finding the most suitable solution for local system challenges from a multi-dimensional perspective.

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