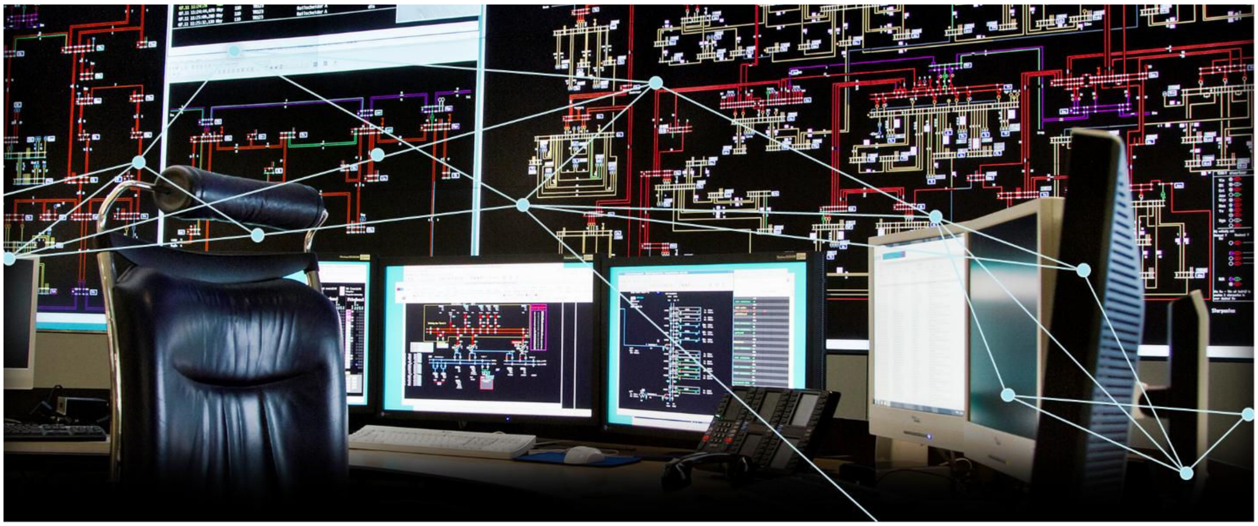
E.DSO Technology Paper

Active Distribution Network Management in Low Voltage Grids



This paper was prepared by members of the European Distribution System Operators (E.DSO) Technology and Knowledge Sharing (T&KS) Committee. E.DSO gathers 35 leading electricity distribution system operators (DSOs) cooperating to ensure the reliability of Europe's electricity supply for consumers and enabling their active participation in our energy system. The T&KS Committee of E.DSO is the reference point for discussion on technical topics that impact the development of smart distribution grids and aims to provide guidance to E.DSO members as they face the technological challenges brought by the energy transition.

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1. Introduction

European low voltage (LV) grids will be subject to huge changes related to the integration of high-power, flexible devices like hybrid or electric heat pumps, photovoltaic (PV) systems, home storage, electric vehicle (EV) charging and, after 2030, vehicle-to-grid (V2G). While these changes can rapidly accelerate when financial or regulatory conditions and public standards become favourable, the speed of uptake of these new high-power devices often cannot be matched by the increase in grid capacity. If not properly tackled, in the coming decade, this will lead to a surge in security of supply risks in local, LV grids.

To the advantage of DSOs, the new high-power devices allow for a high amount of operational flexibility, opening new opportunities to increase the hosting capacity of LV grids as an alternative to grid reinforcement. However, this potential is hindered by the minimal or often complete lack of power flow and voltage control options and near real-time measurement data in LV grids. This makes the subject of LV Active Distribution Network Management (ADNM) of utmost importance and challenging at the same time.

In fact, to manage large numbers of high-power, flexible devices, DSOs need to develop capabilities and tools fostering a transition from passive to active LV network management. As a consequence of this transition, the operational timeframe will more and more approach the one of real-time network management and interaction with distributed intelligence at customer sites (e.g., Home Energy Management Systems - HEMS)[1].

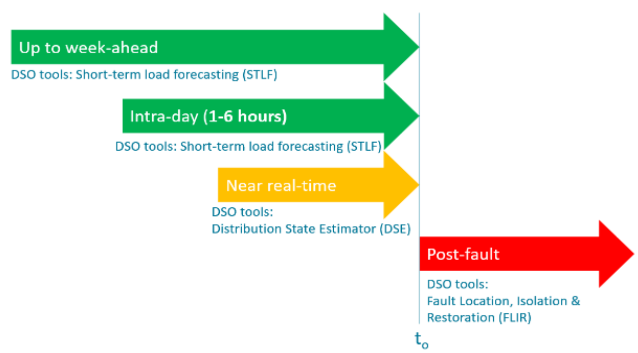

Figure 1-1. DSO tools for active network capacity management

Home Energy Management systems can extend the ADNM systems in the traditional DSO control rooms to the customer side of individual connections. Creating an integrated virtual ADNM system that optimises the regional and individual customer needs for sustainable energy within the technical limitations of the LV networks. At the same time, HEMS systems are the user interface of customers. Their ease of use will determine the acceptance of more real-time flexible capacity management in ADNM, which would allow reaching higher degrees of optimised grid capacity usage. To scale up the market, new propositions from energy markets and network operators are needed. Together with industry, the European DSOs have a pace-setting role, both on the technical prerequisite and contractual propositions from network operators.

This technology paper summarises the findings and recommendations drawn from an E.DSO knowledge-sharing session on the topic of LV ADNM (*Chapter 2*), leading to the conclusion that LV ADNM will be of strategic importance for DSOs and, therefore, shall become a key focus of E.DSO's stakeholder management activities. The paper further elaborates on the results of a members'

[1] Example of multi time scale ADNM : chapter 7 dissertation Grid Edge Control.

questionnaire on the topic (*Chapter 3)*, the outcomes of the sessions' discussion (*Chapter 4)* and three case studies presenting the latest developments and strategies implemented by E.DSO members on the subject (see *Chapter 5*).

2. Findings and recommendations

This E.DSO knowledge-sharing sessions concluded that ADNM will become an essential capability for DSOs to manage the expected increase in low-carbon technologies connected to their grids effectively and in a timely manner, preventing congestion in LV grids and inefficient grid investments. However, the capability for ADNM still requires significant further developments on the DSO side and in coordination with market players and prosumers, which shall be guided by a suitable political framework.

In this context, the Technology & Knowledge Sharing Committee of E.DSO identified the following findings and recommendations.

Innovative concepts for ADNM

- ADNM requires **intelligent forecasting of grid conditions** on timescales that range from several days ahead to near real-time. **Distribution system state estimation (DSSE) and short-term load forecasting (STLF) tools** are important to enable accurate LV network management.
- STLF and DSSE alone do not ensure effective ADNM. High-power **low-carbon technology devices** like EVs, heat pumps, home batteries and rooftop PV **need to be interfaced for automatic response** to strike the right balance is defining safety margins for STLF and DSSE predictions. While too large safety margins will unnecessarily increase grid tariffs and societal costs, too small safety margins will increase the risks to the security of supply.
- The adoption of **model-based tools** must go **hand-in-hand** with the use of **data from measurement devices** for effective digitalisation. This combination can assist DSOs in optimising metering device placement in the grid, fraud detection, and power system simulations.

Regulatory aspects

- As LV grids transition from passive to ADNM systems, digitisation and flexibility activation costs will constitute a larger share of the cost base of DSOs. This should be taken into account in **DSO remuneration methods and tariff calculations** with a move from Capex to Totex methodologies.
- **Open interface protocols for energy management** are essential to scale ADNM to low-carbon technology devices, empower citizens to unlock their flexibility potential and avoid technical lock-ins. As current interfaces are far from being open, regulatory measures, preferably at the EU level, are needed to make these sufficiently attractive for manufacturers.
- **Performance or service level flexible capacity contracts** guaranteeing sufficient comfort to the end user are common in the IT and telecom industry. Applying these concepts to grid capacity contracts for prosumers will enable advanced ADNM and optimisation of both energy costs and required grid capacity. **Regulatory sandboxes** are needed to increase the speed of development and scale-up of these new concepts.

The role of DSOs

- DSOs need to provide **implicit and explicit flexibility activation propositions** to provide a sustainable incentive for prosumers to invest in flexibility control, thereby enabling ADNM.
- STLF and DSSE are not yet mature enough for their full-fledged use in distribution grids, with over 70% of E.DSO members indicating a low degree of use or complete lack of DSSE tools. With respect to this, DSOs will benefit from **sharing experiences on technical solutions for ADNM**.
- E.DSO should take an active role in identifying the DSO interests and setting a **joint action agenda with European manufacturers and the European Commission** on fostering the availability of standard open energy management interfaces for low-carbon technology devices in the residential sector.

3. E.DSO Survey Results

In preparation for the knowledge-sharing session, E.DSO launched a survey to gather the **integral strategic approaches adopted by E.DSO members for LV grid management and the portfolio of concepts they deploy.**

The survey first produced an overview of the **strategies adopted or under development by DSOs for LV grid management** and the **key innovative concepts** they are based on. Most of the respondents highlighted the adoption of a multifaceted approach and a combination of solutions to tackle the challenges of LV grid management. Among these are:

- **Long-term investments** in infrastructure coupled with **short-term solutions** fostering digitalisation and resilience of the network.
- The adoption of **flexibility solutions** including flexible (non-firm) connection agreements, flexibility markets, demand management, and ADNM.
- The adoption of improved **generation and load forecasting methodologies**, capable of modelling the future uptake of low-carbon technologies and electrification of demand.
- Solutions for improving **observability, monitoring and control of LV grids** leveraging smart meter and smart secondary substation data as well as emerging technologies such as artificial intelligence (AI).
- The **integration of technical solutions with regulatory ones**, including flexible tariffs and the use of regulatory sandboxes.

The survey further investigated the **impact of LV grid management challenges on citizens**, with E.DSO members pointing out lengthy and costly network connections, curtailment of photovoltaic (PV) generation and difficulties in achieving national energy targets as the main hurdles. To minimise negative effects on their customers and improve the management of their expectations and needs, DSOs have put in place the following solutions:

- **Communication campaigns** to educate customers on their role in the energy transition, explaining the potential benefits and impacts and informing them about (multi-)annual DSO network plans.
- Engagement strategies to **encourage demand shifting, response to incentive pricing** and **reporting of the installation of new low-carbon technologies**.
- **Simplified and transparent connection processes** and temporary solutions to relieve long connection times such as flexible connection agreements.

Lastly, the survey looked into the needs of DSOs for cooperation and support from other stakeholders. The main identified needs, clustered by stakeholder, are listed below.

- National Regulatory Authorities and governments:
  - Promote **regulatory developments** supporting the solutions identified above (e.g., flexible connection agreements or demand response mechanisms based on congestion services market platforms).
  - Enforce **grid code compliance** on low carbon technologies registration and demand side response qualification.
  - Put in place **simplified and faster licensing and permitting procedures**.
  - Ensure that DSOs have access to **smart meter instrumentation and consumption data** to implement ADNM without the need for extensive measurement investment programs.
  - Be open to **dialogue on DSO investment needs,** allowing them to invest in forecasting tools, active distribution network management, digitalisation and necessary reinforcement.
- European Commission and Institutions:
  - Put in place **stable long-term policies** to secure investments, based on a cross-functional and cross-sectorial approach to the energy transition.
  - **Enforce open** and preferably standardised **energy management control interfaces** for new low-carbon technology devices.
  - Continue **funding DSO-related R&D projects supporting the energy transition of the built environment.**
  - Put in place common **smart grid indicators** to support and benchmark investments in smart grid implementation and customer product offerings.
- Industry:
  - Be open to **innovation that fulfils the real needs of DSOs**, e.g. cooperate with DSOs for the development of **flexibility solutions**.
  - Develop **solutions to optimise customers' (self-)consumption** that support them in taking an active role in the energy system.
  - Cooperate with European DSOs to accelerate the development and implementation of open energy management interfaces for low-carbon technology devices.
  - Develop ready-to-implement **solutions for smarter grid and asset management**, **congestion and voltage control**.

4. Summary of knowledge-sharing session discussions

The discussions during the E.DSO knowledge-sharing session dived deeper into three concepts related to LV ADNM.

The first addressed topic was **short-term load forecasting**. The outcomes of this discussion are summarised in Figure 4-1, looking at (a) the most promising use cases for STLF, (b) actions for mitigating DSO forecast error risks, and (c) actions carried out by DSOs as part of their STLF implementation strategy. Solutions for the mitigation of STLF errors were clustered in four categories: **AI and generative AI**, **data**, **flexibility** and **last-resort solutions**. With the objective of increasing the accuracy of STLF models, participants recognised the importance of two main elements: the **improvement in weather forecast models** and the **quality and availability of data**. A greater difficulty in achieving high accuracy at the local level was pointed out, due to the intrinsically lower availability of data. The incorporation of **non-energy data** in STLF models was also suggested as a solution.

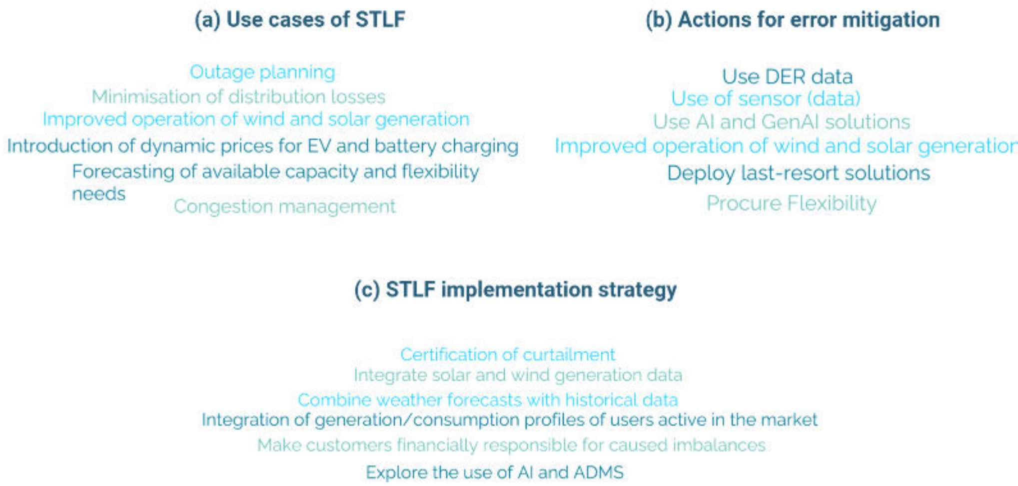

Figure 4-1. STLF: (a) Most promising use cases, (b) actions for error risk mitigation, and (c) implementation strategy actions by DSOs.

The second addressed topic was **distribution system state estimation**. Most DSOs reported being in the early stages of implementation, with several not having initiated them yet, as shown in Figure 4-2. Different barriers to the adoption of digital technologies by DSOs are also discussed, as reported in Figure 4-2. Economic aspects are reported by the members to be the most significant barrier, followed by technical and organisational barriers. In terms of most promising use cases for DSSE tools, members highlighted **fraud detection**, **data enhancement**, **simulation** purposes (in combination with power flow calculations), and **real-time control**.

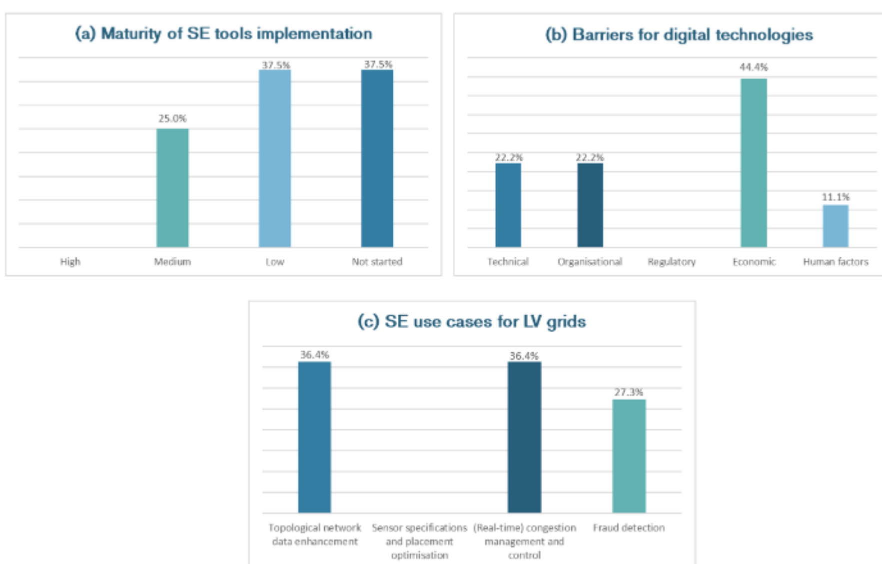

Figure 4-2. DSSE: (a) Maturity of DSSE tools implementation, (b) barriers to the integration of digital technologies in distribution grids, and (c) most promising use cases in LV grids.

The third topic addressed the role of **Home Energy Management Systems** in the combined optimisation of capacity management in LV grids and residential energy costs (see Figure 4-3). For some DSOs, these HEMS will not compete with cheaper and aggregator-based device applications, considering that most of the flexibility in LV grids will be offered by EVs and home batteries. However, the majority of DSOs foresee that HEMS will take a prominent role, providing **integral control of home devices** and fostering additional financial benefits and self-consumption of sustainable energy. On the other hand, some DSOs believe that congestion services will scale up to become the dominant approach to LV capacity management thanks to solutions developed by independent aggregators. Others consider the uncertainty associated with home device flexibility activation too high for DSOs to rely on them. The development of a **standardised open flexibility interface for device interconnection** and **dialogue with energy suppliers and aggregators** were suggested as solutions to support the uptake of LV capacity management services.

As a last point, **the role of DSOs in home energy optimisation** was addressed, with some respondents supporting a fully market-led approach (i.e. led by supplier and aggregator propositions). However, the majority advocated for **a stronger involvement of DSOs** in the development and standardisation of flexibility market frameworks, flexible connection agreements and HEMS-DSO interconnection standards.

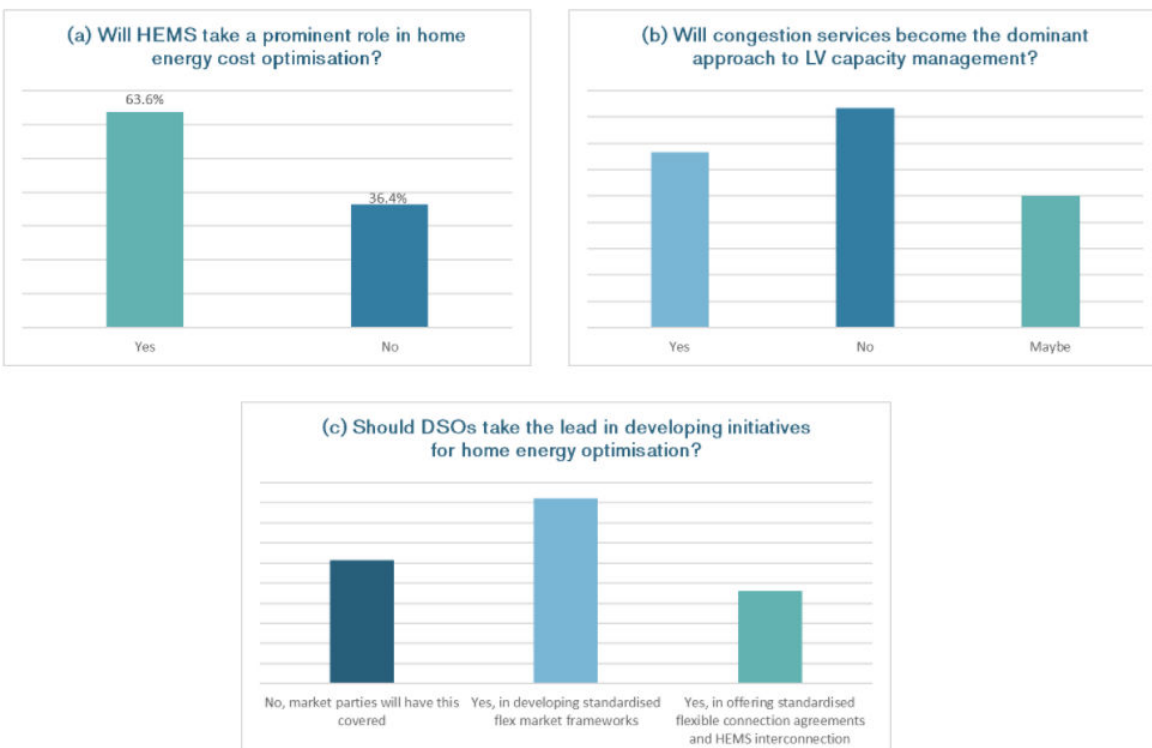

Figure 4-3. Outcomes of the discussion on HEMS and LV congestion services.

5. Case studies

5.a. Case Study 1: Sadales Tikls "Short-term load forecasting"

Short-term load forecasting typically refers to a time between minutes-ahead to week-ahead, but each system operator will select the optimum forecasting horizon based on the use case. STLF is a critical solution for DSOs to enable ADNM and support:

- **Flexible connection agreements**, by minimising customer capacity restrictions and curtailment.
- **Flexibility services**, by minimizing flexibility activation costs to DSOs.

With the uptake of variable renewable energy (VRE), load forecasting has become intrinsically difficult as it requires good solar radiation and localised wind speed forecasts. As VRE reduces forecast accuracy, Sadales Tikls studied its impact on transformer load forecasts and options to mitigate forecast errors. Before applying the forecasts to the LV network, MV-level forecasts were tested with available real-time Supervisory Control and Data Acquisition (SCADA) to drive the STLF algorithm. Forecast uncertainty is one of the limiting factors for fast-tracking grid flexibility as inaccurate forecasts (Figure 5-1) pose:

- **Technical risks**, if the forecast does not capture peak load hence preventing flexibility activation and causing asset overload; or
- **Financial risks**, if the predicted network congestion does not occur, triggering false flexibility activation and associated flexibility payments.

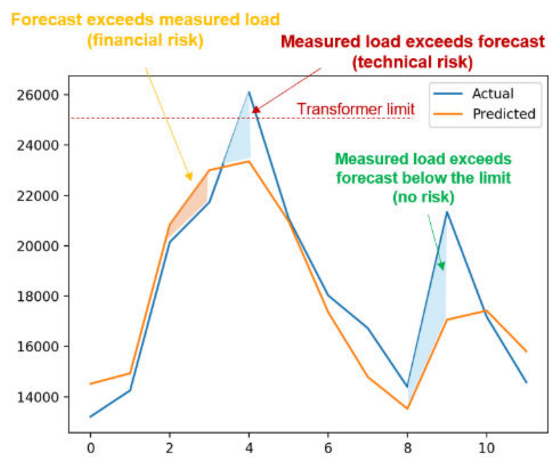

Figure 5-1. The impact of forecast uncertainty.

Sadales Tikls completed a 9-month pilot project with two load forecast providers to evaluate STLF accuracy (*p50*[2] baseline) for solar and wind farms and primary transformers with high VRE penetration. Various accuracy metrics were applied (MAE, RMSE), but Mean Absolute Percentage Error (MAPE) results are shown in Figure 5-2. All five solar farms showed similar results with 4h-ahead average forecast error ranging between 20-30%. It should be noted that Vendor #1 was new to solar generation forecasting, while Vendor #2 had over 10 years of experience. While Vendor #2 performed better on average, the results showed that meaningful skill performance can be achieved relatively quickly. The higher variation in results for Vendor #1 was likely due to the use of physical solar farm models (e.g. solar panel layout, inverter model), while Vendor #2 relied only on a statistical model.

For primary substations, load forecasts can be provided as the difference between demand forecasts and generation forecasts from utility-scale solar and wind farms. The MAPE score of apparent power was lower than for solar generation forecasts but with a noticeable variation in results. The lowest error was observed for a substation with utility-scale solar PV (Ast99), while wind forecasts turned out to also affect primary load forecasts (Ast60). Given the forecast error variation in low-generation

[2] 50% probability of load exceeding the forecasted value.

and high-generation hours, Sadales Tikls is now working towards *p10*[3] forecasts and dynamic safety margins to minimise the risks of under-forecasting transformer loads.

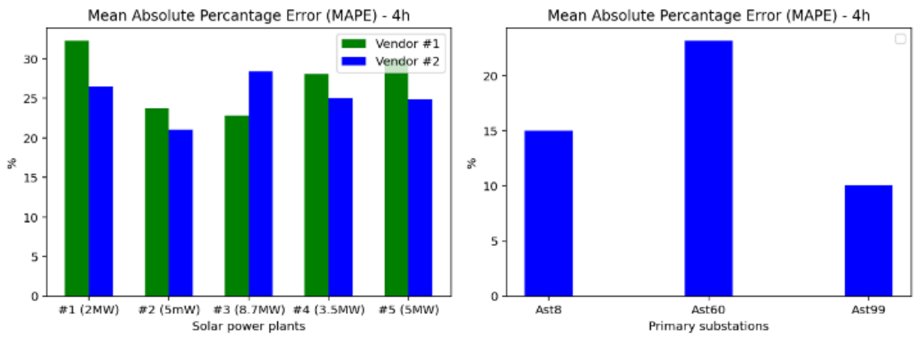

Figure 5-2. Mean Absolute Percentage Error (MAPE) results for STLF on solar power plants and primary substations.

Conclusions.

- **Rolling horizon load forecasts** are required, preferably relying on weather forecast providers who utilise **satellite images on top of climate models**.
- **Statistical forecast models should be preferred** over physical ones. While suitable for plant operators, DSOs cannot build physical models for hundreds of VRE plants considering site layout, angle, efficiency of inverters, etc.
- The Sadales Tikls pilot relied on *p50* forecasts, while **DSOs should consider *p10* forecasts** since the main objective is to predict and mitigate the peak load.
- **Day-ahead & intra-day market prices should be included in the forecasts** as the curtailment or switch off of commercial VRE sites at times characterised by negative prices significantly affect VRE predictability.
- STLF can be applied in LV networks as in MV networks as long as **real-time data from the transformer** are available.

5.b. Case Study 2: Stedin “Distribution system state estimation and grid observability for capacity management, monitoring and control of LV grids”

Electrification and the resulting proliferation of distributed energy resources (DERs) such as solar PV, EVs, and heat pumps necessitate capacity management, congestion and voltage monitoring and control of LV grids. Conventional network design in the Netherlands assumes ca. 1.5 kW of simultaneous power usage per household. Towards 2035, it is estimated the grids to need to accommodate 5 kW per household at a given moment in case of full-electrification and without considering any time-shifting through demand-side flexibility [4]. Moving towards 2035, however, it is estimated that this value will rise to 5 kW per household in case of full electrification without considering consumption shifting through demand-side flexibility. This trend underscores the increasing importance of ADNM in LV grids and of **enhanced grid visibility through digitalisation** as one of its main pillars.

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[3] 10% probability of load exceeding the forecasted value.

[4] Source: Januari 2024, Probleemanalyse Congestie in het Laagspanningsnet Opgesteld onder leiding van Stephan Brandligt, onafhankelijk coördinator Actieagenda Netcongestie Laagspanningsnetten. Available at: Probleemanalyse Congestie in het laagspanningsnet.

In the Netherlands, grid digitalisation is already taking pace. Nevertheless, only a quarter of the MV-LV transformers are currently equipped with a sensor [4]. This implies that, with the current digitalisation level of the grid, tracing which cable or connection encounters problems at a given time can be challenging. In addition, DERs tend to have dynamic characteristics and introduce the possibility of power flow reversals which affect protection and control regulation. LV networks are usually not equipped with advanced monitoring systems and devices providing insights into these dynamics.

Observability of the grid relates to the availability of sufficient measurements to predict the most likely state of the grid (expressed in terms of voltages, phase angles, currents, and active/reactive power flows). In this context, state estimation has been used by transmission system operators for over 50 years in their daily operations. Conventional methods for estimation based on classical statistical techniques, necessitates a redundant number of measurements as well as their adequate dispersion across the grid. Distribution system operators, on the other hand, started adopting state estimation tools for distribution systems within the last 15 years. Low observability of LV grids is a challenge. Nowadays, AI-based state estimators for networks with limited observability are being developed, though they are not mature yet for their full deployment.

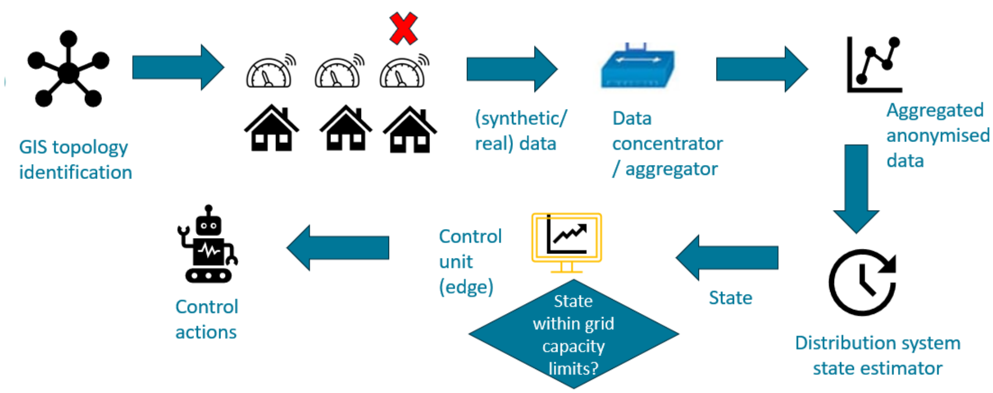

Figure 5-3. Conceptual framework on distribution system state estimation using aggregated and anonymised smart meter data.

Figure 5-3 outlines a future perspective of grid active capacity management concepts. Firstly, DSOs leverage Geographical Information Systems (GIS) to collect grid topology data. GIS data is then incorporated with real-time data from sensors and other monitoring tools. Given the dynamic changes in LV grid connections and topologies caused by network upgrades and reconfigurations, AI-based DSSE tools are deployed to enhance topology data and allow for feeder identification of grid connections. Additionally, smart meter data, aggregated and anonymised through a data concentrator, is used to improve the forecasting of loads and generation fed from the LV grid. AI or other statistical machine learning-based tools can assist in filling in missing data points. These tools can also be applied to networks with a high degree of observability. This is because measurement devices can be subject to data errors or noise (e.g., due to communication faults and varying error tolerances among different devices). Furthermore, aggregated and anonymised data can be used as input to a DSSE tool, supporting capacity management. Finally, control centres or control units at the grid edge (i.e., at the substation level) equipped with a state estimator would be able to use DSSE results to check whether electrical parameters (e.g., active/ reactive power or voltage) are within normal limits. With accurate estimates, the control unit would be able to perform appropriate congestion and voltage management and control.

Conclusions

- The adoption of **model-based tools must go hand-in-hand with** the use of **data from measurement devices** for effective digitalisation. Such tools will assist in, among others, identifying measurement errors and filling in missing data points.
- **DSSE is not yet mature enough for its fully-fledged use in the distribution grids**. In fact, more than 70% of E.DSO members attending the knowledge-sharing session indicated either having a low usage of DSSE tools or not having started the implementation of such models yet (see Figure 4-2).
- Research and innovation on model-based approaches to estimate grid state, potentially incorporating AI at the grid edge, support **effective distribution system operations and control for grids with a high degree of DERs**.
- In addition to data quality enhancements, DSSE tools can assist DSOs in **optimising metering device placement in the grid, fraud detection, power system simulation** (dynamic and data-driven power flow calculations), **and real-time control**.

5.c. Case Study 3: Alliander "HEMS for advanced LV Active Distribution Network Management"

New high-power low-carbon technology devices acquired by prosumers in Dutch households are equipped, in principle, with extensive technical control options which can be integrated into simple controllers or more advanced **Home Energy Management Systems.** Framework and incentives provided by electricity markets and DSOs will determine the actual deployment of the flexibility of these devices. Presently, the Dutch framework hardly presents any DSO-related incentives and even the present residential grid tariff does not give an incentive as it consists of a flat fee tariff independent of the use of capacity or energy.

Implicit flexibility incentives

Implicit incentives foresee an incentive in the Dutch grid tariffs based on a Time of Use (ToU) methodology. **ToU tariffs** are a simple and effective incentive measure to which people can react with and without (home) automation systems. The Dutch DSOs have conducted a study[5] on an hourly varying tariff for the kWh consumed revealing that:

1. The tariff incentive leads to **a more grid-friendly deployment of flexibility**, lowering the annual peak demand for grid capacity by around 10%.
2. A **fairer cost allocation of grid fees**, as with the new tariff, also **reflects the intensity of grid usage by people**. This aspect is important for social acceptance of the energy transition.
3. The tariff creates an **additional stable business case for flexibility optimisation** of people's low-carbon technology assets.

Explicit incentive: performance-based capacity contracts

As part of the explicit incentives, Alliander takes into consideration conventional congestion services and flexible capacity contracts, as used in MV grids and for large industrial customers. However, the Dutch DSO believes residential customers to have different interests which requires a new thinking framework leading to the concept of **"service level" or "performance" based flexible capacity contracts**.

[5] Source: https://www.netbeheernederland.nl/publicatie/berenschot-verkenning-alternatief-nettariefstelsel-kleinverbruik

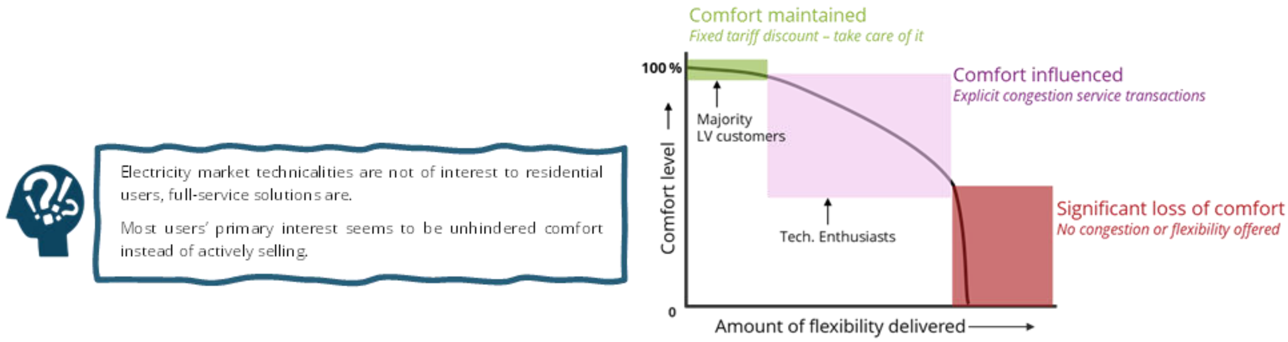

Figure 5-4. Conceptual framework for residential flexibility.

As illustrated in Figure 5-4 most residential customers value their comfort much more than the relatively small financial reward they can gain through flexibility services. To explore the potential of a performance-based flexible capacity contract, Alliander started investigating whether a "comfort"-based contract would lead to higher societal benefits and hosting capacity for low-carbon technology devices in the existing LV grids[6]. This would enable an accelerated energy transition while safeguarding fair remuneration and cost allocation to consumers. To this end, Alliander developed an **LV Digital Twin**.

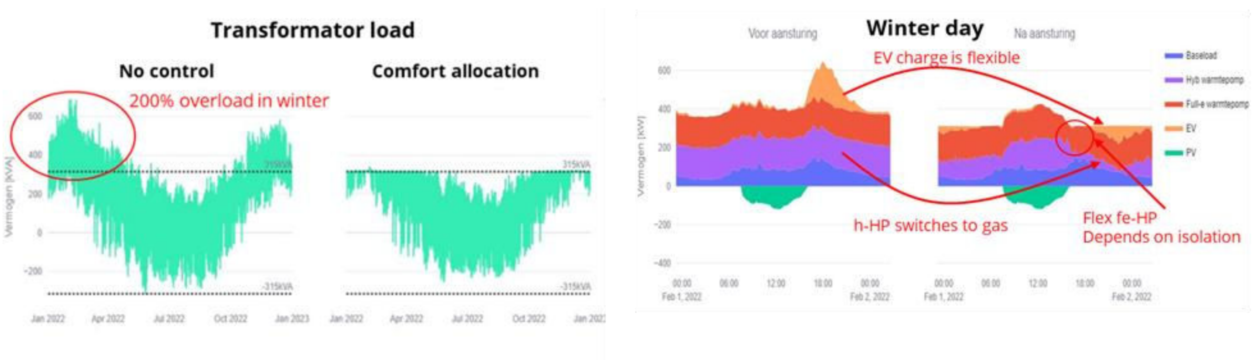

Figure 5-5. Simulation of potential performance based on capacity contracts.

The investigated performance contract assumes a fixed discount on the grid tariff and guarantees for allocation of sufficient capacity by the DSO to meet the agreed performance levels of the customer. For instance, the contract could ensure the house temperature varies by no more than 1°C and the EV is charged by 6 a.m. for at least 150 km range. Assuming that the majority of residential customers would be interested in such a contract, Alliander simulated different 2040 scenarios to see the impact on hosting capacity while meeting all the agreed performance KPIs. The results showed that by applying active distribution network management with optimised capacity allocation, the performance requirements can be met with significantly less grid capacity than the simultaneous 5kW household loads anticipated to be necessary with the present fixed capacity contracts. These results underlie the potential of performance-based contract concepts.

Market developments for performance-based contracts

The described "performance" contracts require HEMS technology to manage in-house comfort levels while facilitating a privacy-friendly and simple "capacity bandwidth" interface to the DSO. Existing

[6] Article: towards congestion management in distribution networks a Dutch case

flexibility market players, however, are mainly single-device-type-based aggregators, controlling geographically distributed devices that they offer as a capacity response in different markets. Currently, most aggregators lack an integrated home flexibility offering that enables the described performance-based flexibility contracts. This raises the question of which market players would step in to drive these new propositions and what their timeline is for scaling. To explore a pathway to this emerging market and which market players will take the lead in it, Alliander created an innovation community with energy suppliers, big tech companies, and several multi-device aggregators.

Conclusions

- ADNM in LV shows significant potential to increase the hosting capacity for new high-power low-carbon technology devices. **Performance-based capacity contracts** appear to be closely aligned with the primary interests of residential prosumers.
- **Open interface protocols for energy management** purposes are a prerequisite to valorise the potential of residential flexibility. Open interfaces are also essential to empower citizens to make their own choices in unlocking their flexibility in the energy system and avoiding lock-ins.
- As current interfaces are far from being open, **regulatory actions** are needed to make these sufficiently attractive for standardisation by manufacturers, preferably at the EU level.
- More advanced performance-based capacity contracts require **HEMS technology to manage in-house comfort levels while facilitating a privacy-friendly and simple "capacity bandwidth" interface to the DSO.** The existing market players, however, are mainly focused on single-device-type aggregator propositions. **It is uncertain which market players will take the next step** to integrated energy propositions and with which speed.