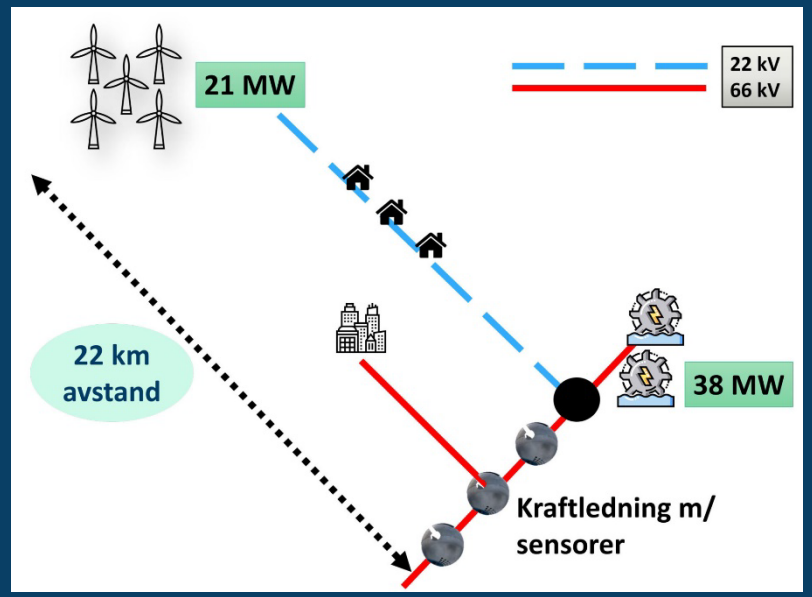

CINELDI
Centre for intelligent electricity distribution
- to empower the future Smart Grid
Norwegian Centre for
Environment-friendly
Energy Research
Selected CINELDI Results 2023
for external use

CINELDI result: Analysis of sensor data for dynamic line rating (WP1/WP Pilot)

Challenge and objective:

- In a CINELDI pilot, sensors on power transmission lines monitor the internal temperature of the lines. The objective was to investigate whether it would be feasible to allow higher power transmission from the wind farm, as the power lines are cooled by the same wind responsible for wind power generation.



Work performed:

- Data from the sensors were combined with meteorological data, production data and load flow to investigate the correlation between them.

Significant results:

- A greater proportion of wind power in the load on the line lead to lower line temperatures due to the correlation between wind power production and wind-induced cooling.
- A machine learning model was trained to predict line temperature based on the provided data, acting as a virtual sensor.

Impact for distribution system innovation:

- This demonstrates the usefulness of dynamic line rating, and can contribute to accelerated integration of wind power in the power system.

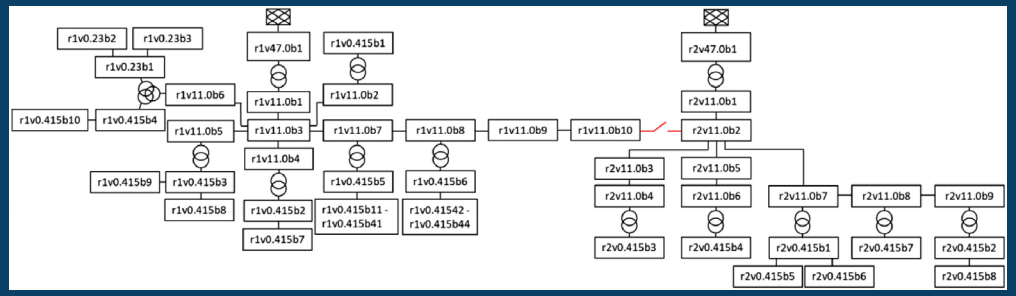
Reference in CINELDI:

- The work was presented in a #SINTEFblogg post https://blogg.sintef.no/sintefenergy-nb/bedre-utnyttelse-av-stromnettet-med-dynamiske-kapasitetsgrenser/

CINELDI result: Dataset for a Norwegian medium and low voltage power distribution system with industrial loads (WP1)0

Challenge and objective:

- Although test grid models are available online, they are typically not representative for real grids. The strength of this reference grid and load data is that they describe a real, Norwegian grid with both commercial and industry loads, with hourly load data collected over three years.



An illustration of the industrial distribution grid dataset.

Work performed:

- Grid and load data for a real grid were converted to a MATPOWER grid model, simplified and anonymized.

Significant results:

- A MV-LV distribution grid and load data set was established and published openly, providing useful test data for research and innovation purposes.

Impact for distribution system innovation:

The dataset can be used to:

- Analyze historic load behavior or predict future behavior.
- Analyze the need for power system flexibility and reliability of supply.
- Test methods for grid planning.
- Develop methods and tools for finding remaining grid capacity.

Reference in CINELDI:

- S. Sandell, D. Bjerkehagen, B. Birkeland, I. B. Sperstad, (2023). Dataset for a Norwegian medium and low voltage power distribution system with industrial loads. Data in Brief, 48, 109121. https://doi.org/10.1016/j.dib.2023.109121 and presented in blog post https://blogg.sintef.no/sintefenergy-nb/smartgrids/hvorfor-publisere-nett-og-lastdata

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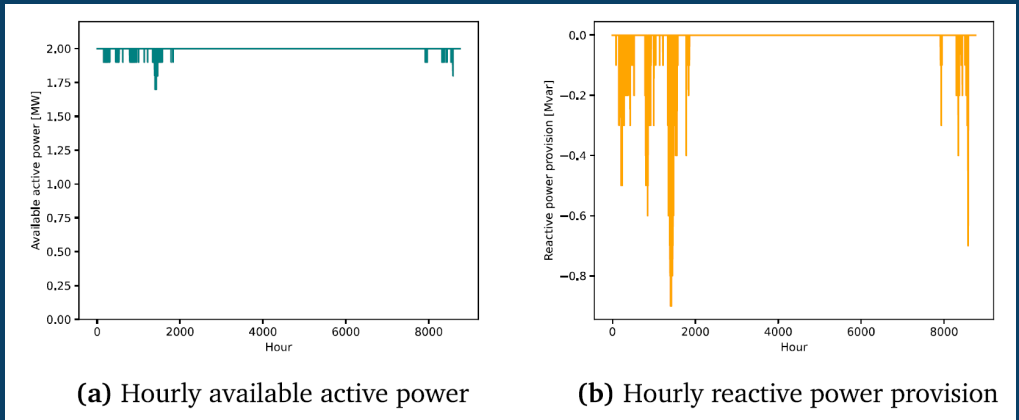
CINELDI result: Alternative grid connection agreements for integrating fast-charging stations in the distribution system (WP1)

Challenge and objective:

- Integrating fast-charging stations (FCS) in the distribution system using traditional grid connection agreements often requires grid reinforcement to avoid overloading and undervoltage problems. This leads to delays and additional costs for deploying charging infrastructure to support the rapid increase in adoption of electrical vehicles.
- The potential of *alternative* connection agreements between FCS operators and DSOs is explored.



(a) Hourly available active power **(b)** Hourly reactive power provision

Work performed:

- A methodology is developed that models active load curtailment and reactive power provision from FCSs as active measures to avoid undervoltage, using load and grid data available to DSOs as inputs.

Significant results:

- Applying the methodology to the CINELDI reference system, it is found that a 2 MW FCS can be connected with the condition of active measures activated for just around 4% of the year.
- For the rest of the year the FCS can consume power at full capacity without triggering voltage problems.

Impact for distribution system innovation:

- Alternative connection agreements have great potential but requires additional analyses and communication between the DSO and the FCS operator. This work gives an example of analysis results that can support the DSO in designing the conditions of the connection agreements.

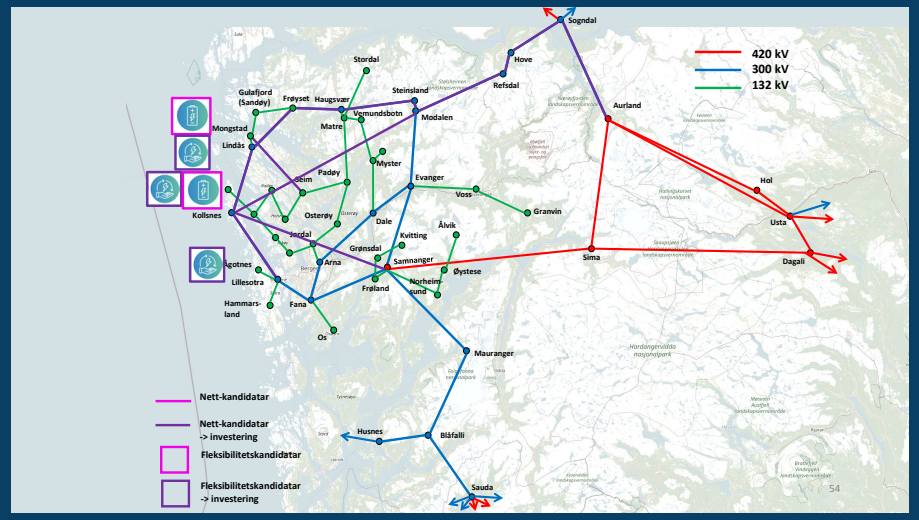
Reference in CINELDI:

- Anna Liv Leikanger Aasen, "Integration of fast-charging stations in the distribution system – Exploring the potential of alternative grid connection agreements", Master thesis, NTNU Dept. of Electric Energy, 2023.

CINELDI result: Grid planning case study in the EU project FlexPlan considering a region in the Norwegian power grid (WP1)

Challenge and objective:

- The goal of the EU project FlexPlan was to develop methodology and tools for grid planning taking into account flexibility resources as a supplement to traditional grid reinforcement/expansion. One hypothesis is that using flexibility reduces the need for grid investments.



Work performed:

- Development of planning model and data set in the FlexPlan project (in-kind).
- Development of case in collaboration with BKK Nett.

Significant results:

- Application of optimization of long-term grid planning decisions (grid expansion and/or use flexibility) for transmission grid and regional distribution grid in the BKK area.

Impact for distribution system innovation:

- The role of flexibility is case dependent
- Flexibility can be a *supplement* – and not necessarily an *alternative* – to grid investments.
- Flexibility has limited value in deferring/avoiding grid investments given sustained high load growth .
- Flexibility has limited value for grid areas dominated by industry with flat and inflexible load profiles.

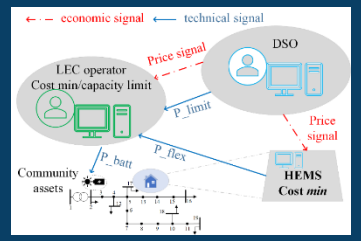
Reference in CINELDI:

- I. B. Sperstad and A. Z. Morch, “Langsiktig nettplanlegging hensyntatt fleksibilitetsressurser – resultater fra FlexPlan-prosjektet”, presented at joint FlexPlan/CINELDI workshop 2023-02-20) and summarized in blog post (https://blogg.sintef.no/sintefenergy-nb/smartgrids/betre-nettplanlegging-med-fleksibilitetsressursar/)

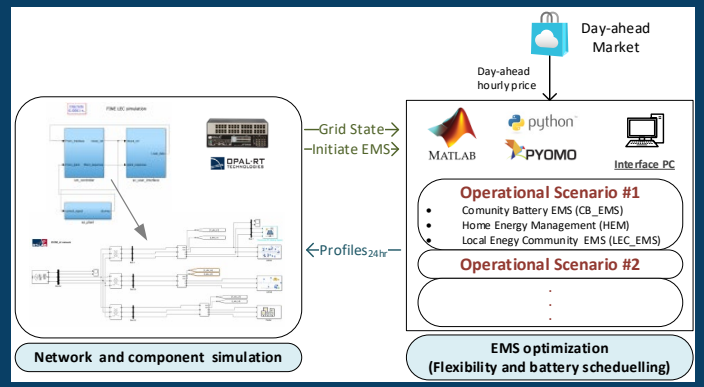
CINELDI result: Demonstrating Interactions of Distribution Network and Local Energy Communities Operating in Hierarchically Autonomous Control Architecture Paradigm (FINE/WP2)

Challenge and objective:

- There are limited physical implementation cases of LECs from which distribution network operators and policy makers can learn.
- The operational interaction between LECs and the distribution network remains largely unaddressed.



Interaction among physical components, controllers, and market with LEC operating in distribution network.



Real-time simulation setup for LEC operations

Work performed:

- A real-time simulation approach is discussed and implemented as a supplementary approach to account for the operational impacts of LECs.
- Hierarchically autonomous Energy Management Systems (EMSs) are implemented together with simulated network to highlight some of the benefits of such high-fidelity simulation studies.
- Specifically, a CIGRE LV network with a LEC on one feeder is studied under different operational scenarios.

Significant results:

- The results highlight issues which might be overlooked when doing active-power-based battery and flexibility scheduling to solve the overloading of MV/LV transformer.
- The simulation results reveal that active power scheduling and planning of flexibility activation based solely on active power may result in overloading or voltage limit violations.

Impact for distribution system innovation:

- A simulation platform has been established to study and demonstrate impact of LECs on distribution network operation.

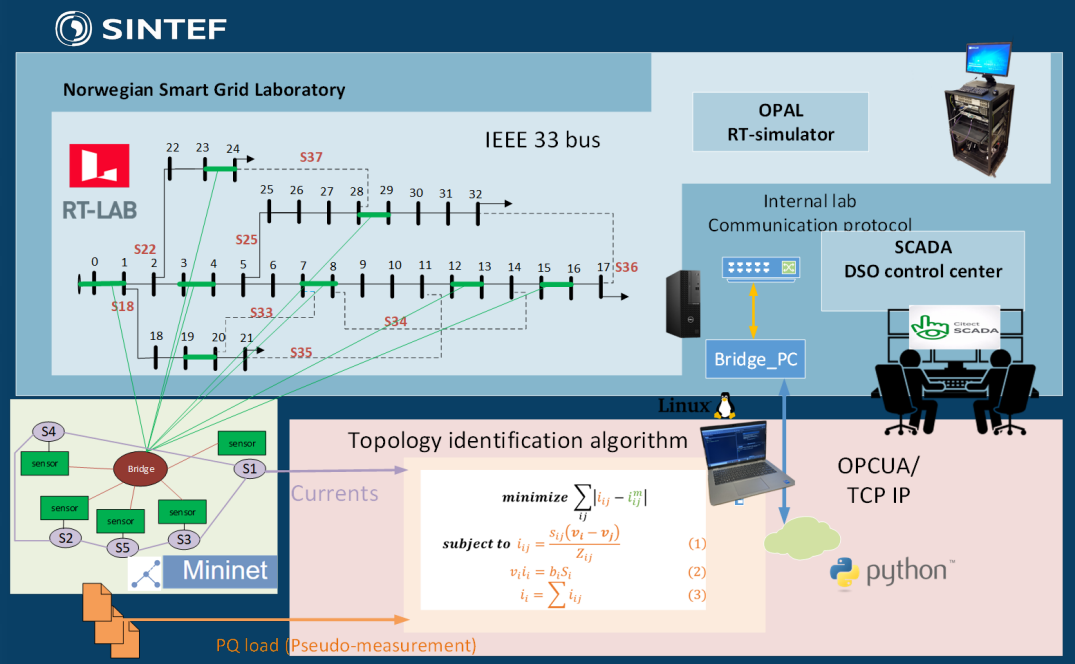
Reference in CINELDI:

- M. Z. Degefa, R. Rana and H. Taxt, "Demonstrating Interactions of Distribution Network and Local Energy Communities Operating in Hierarchically Autonomous Control Architecture Paradigm", CIRED 2023.

CINELDI: Cyber-Physical Power System Testing Platform for Topology Identification in Power Distribution Grids (WP2)

Challenge and objective:

- Knowledge of the grid topology is required for advanced functionalities such as optimal power flow or state estimation.
- This information is often missing, and topology identification (TI) appears as a key component.



Work performed:

- A TI method based on mixed integer linear programming (MILP) is validated for MV and LV systems that can be used in DSO's control centre.

Significant results:

- The algorithm has been challenged by integrating the TI algorithm with a CPPS where the current measurements interact within a communications layer.
- TI accuracy and robustness against error in the sensor and pseudo-measurements are tested in the CPPS platform.

Impact for distribution system innovation:

- The TI algorithm seems to be a practical for integration in the DSO control centre to operate with existing energy measurements from smart meters.

Reference in CINELDI: R. E. Torres-Olguin, S. Sanchez-Acevedo, O. Mo and A. Garcés-Ruiz, "Cyber-Physical Power System Testing Platform for Topology Identification in Power Distribution Grids", *2023 IEEE Belgrade PowerTech*, Belgrade, Serbia, 2023, pp. 1-6.

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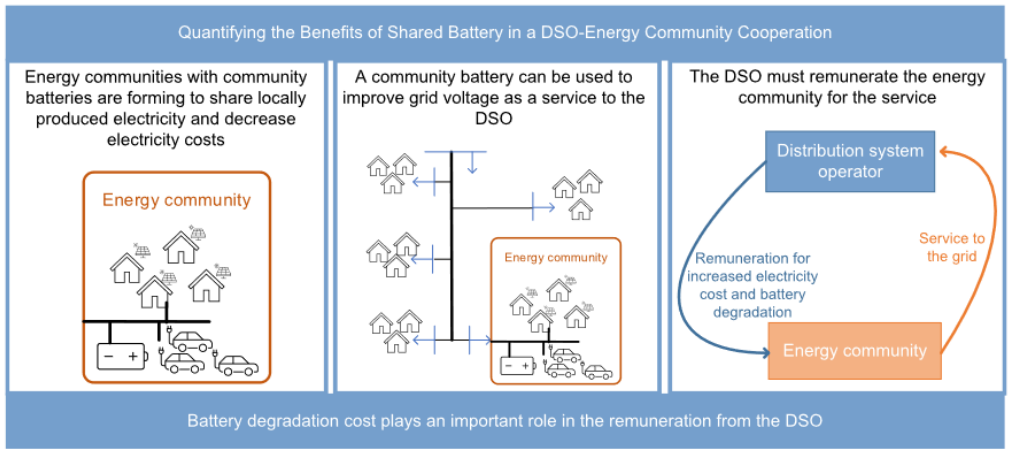
CINELDI result: *Quantifying the benefits of shared battery in a DSO-energy community cooperation* (WP2/FINE, PhD student Kjersti Berg)

Challenge and objective:

- Local energy communities enables prosumers and consumers to invest in renewable energy sources, storage and share electricity.
- Several distribution grids have voltage problems at certain hours of the year.
- Local energy communities consisting of generation and storage units might be valuable flexible assets that the distribution system operator (DSO) can make use of.



Work performed:

- Created a linear optimisation model including power flow constraints and battery degradation and studied a case.

Significant results:

- Voltage violations are sensitive to the battery replacement cost, electric vehicle charging peak and the average spot price, the remuneration from the DSO is sensitive to the battery replacement cost.
- For small battery sizes and a low power-to-energy ratio, the community is not able to improve the voltage at all hours of the year.
- There is an increase in electricity and degradation costs for the energy community (equals 0.12% in the studied case).

Impact for distribution system innovation:

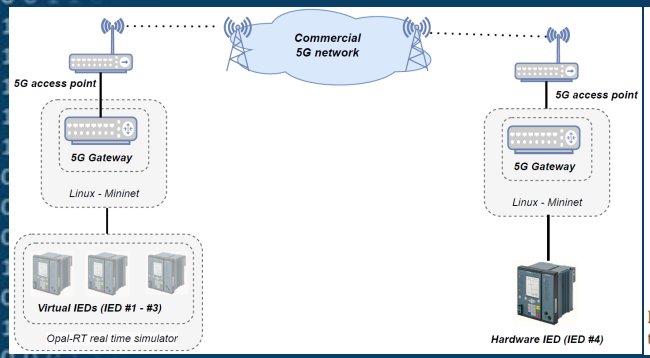
- The work shows how a battery in an energy community can provide services to the grid.

Reference in CINELDI:
K. Berg, R. Rana, H. Farahmand, "Quantifying the benefits of shared battery in a DSO-energy community cooperation", Applied Energy, *343*, p.121105, 2023.

CINELDI result: Testing of GOOSE protocol for outside of substation application over 5G (WP2)

Challenge and objective:

- 5G wireless networks are quickly getting better coverage and becoming a viable alternative for smart grid communication.
- Applications such as self-healing and protection coordination require faster and reliable communication and can benefit from 5G, but need investigation on how to adapt to the service quality that the 5G network can provide.
- This work aims to examine and evaluate the performance of commercial 5G networks for protection coordination and investigate if the protection coordination can be parameterized to work with the 5G network.



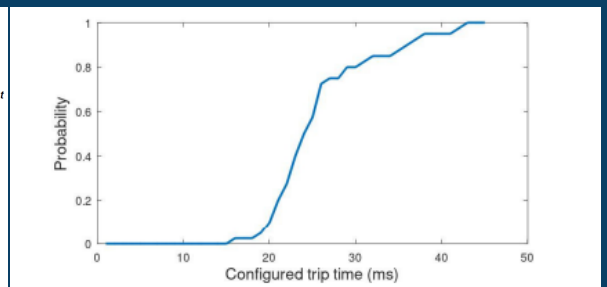


Fig. 5. The probability of blocking the backup IED (avoiding unnecessary trips) as a function of configured trip time.

Work performed:

- An experimental evaluation of protection coordination implemented over a commercial 5G network (non-standalone 5G with LTE-EPC core) with HIL setup consisting of both hardware and emulated protection devices.

Significant results:

- Insights into how protection coordination schemes can use available 5G networks in practice is provided.
- Protection coordination scheme's parameter configuration should rely on the actual performance measurements of the mobile network, considering the uncertainties.
- Using data from the IED position is more suitable than statistics from broader measurement campaigns.

Impact for distribution system innovation:

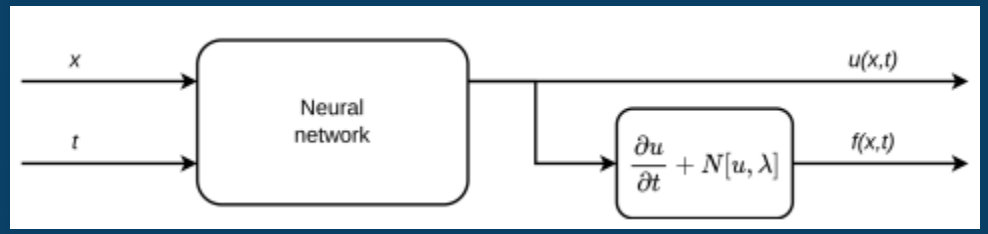
- This study characterized commercial 5G for protection coordination, marking the initial phase in deploying 5G for smart grid applications.
- Use 5G for protection coordination could provide grid companies with a cost-effective and reliable alternative compared to other communication technologies.

Reference in CINELDI: T. A. Zerihun, H. Lundkvist, S. S. Acevedo, "Performance Evaluation of IEC 61850 GOOSE Messages over a 5G Network for Protection Coordination in Smart Grid", IEEE SmartGridComm, 2023.

CINELDI result: Physics informed neural networks in radial load flow calculations (WP2)

Challenge and objective:

- A multitude of different approaches to solve the load flow problem in different power grids exist - some are computationally expensive, but yield exact solutions, others rely on simplifications and are much faster but less accurate.
- Neural networks (NNs) have got popularity within many applications for time critical applications but relies on large amounts of data for training.
- Physics informed neural networks (PINN) use prior knowledge of structural information in combination with available data to boost the training and be less dependent upon large amounts of data.



Flowchart of a physics informed neural network

Work performed:

- Investigated physics informed neural networks to solve load flow in radial distribution grids.
- A major motivation of the work was to gain experience in these techniques for power system applications.
- Tensorflow is used to establish neural networks in Python that are trained to solve load flow.
- The selected approach is tested on a 4-bus test grid and on the radial IEEE33- and IEEE69-bus systems.

Significant results:

- Demonstrated NNs capabilities and challenges.
- The value of including structural knowledge with data and to combine with classical techniques.
- A report giving overview of techniques and discussing applications.

Impact for distribution system innovation:

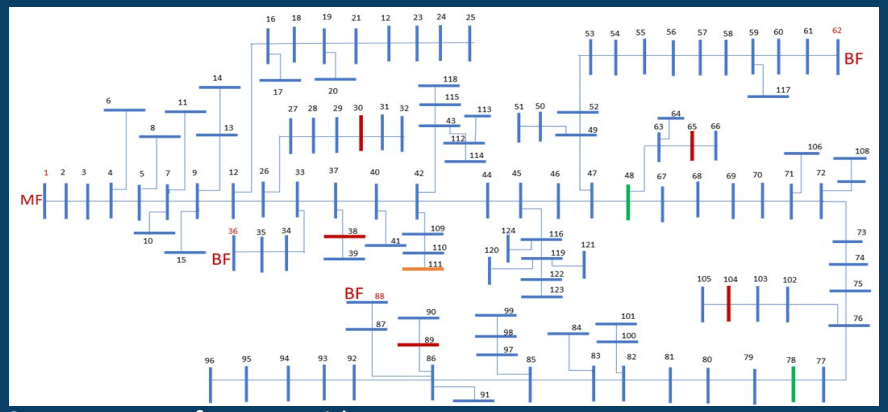
- The gained experiences are important for other applications and further development.

Reference in CINELDI:
Martin Müller: "Physics informed neural networks in radial load flow calculations", Master Thesis, NTNU, 2023.

CINELDI result: Feasibility check of topology changes in radial distribution networks (WP2)

Challenge and objective:

- In radial distribution grids the removal of overloads and voltage problems will in general either reduce the active load, increase the reactive support or change the topology.
- In 2019, the development of PyDSAL (a tool for distribution system load flow) was reported in CINELDI. A core element of this tool was a module for identifying topologies of sub-systems where a load flow was conducted afterwards.



CINELDI MV reference grid.

Work performed:

- The tools was further developed and the topology search algorithms generalized in a specialization project, a MSC-thesis, and in CINELDI.
- The topology module got the ability to build up a sub-system from any feed-in node and then solve the load flow.

Significant results:

- For a radially operated distribution system, the load flow can be conducted for any alternative feed in.
- Any line may be disconnected, and load flow conducted for sub-systems and alternative feed-ins.
- Testing is done for different topologies.

Impact for distribution system innovation:

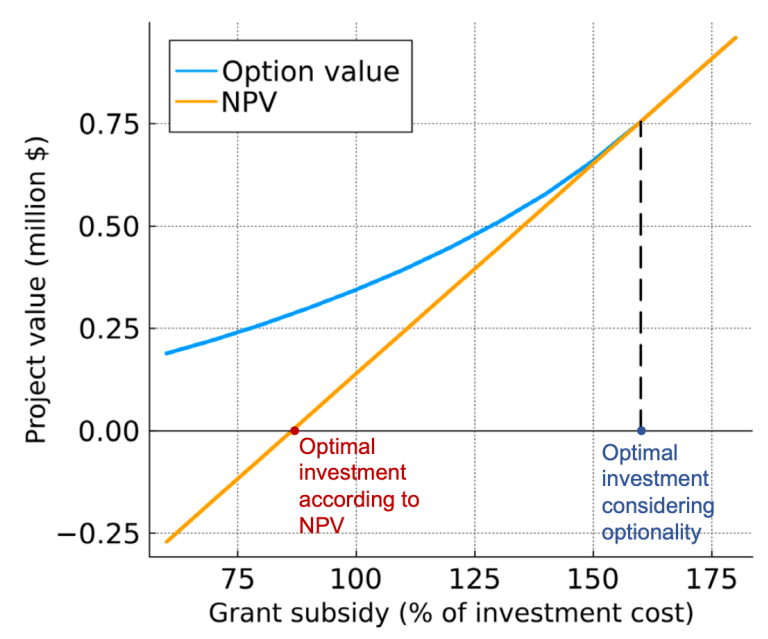
- The topology module and the load flow tool may be integrated in tools where it is a need for checking alternative topologies and the impact of changes.

Reference in CINELDI:
Alvar Øyasæter, "Transition Strategies for Smart Grid: Evaluating future scenarios on a distribution grid", Master Thesis, NTNU, 2022.

CINELDI result: Accelerating electric vehicle charging investments: A real options approach to policy design (WP3)

Challenge and objective:

- Fast charging availability in rural areas is insufficient.
- The commonly used Net Present Value method for understanding the economics of charging investment does not capture the role of uncertainty.



Work performed:

- A model of investment that acocunts for future uncertainty.

Significant results:

- Investors' uncertainty about future EV demand can explain the relative lack of fast charging in rural areas.
- Investments would take place faster if policy makers mitigate investors' risk exposure.
- Long-term contracts are an effective way to reduce investors' risk and thus incentivize investment.

Impact for distribution system innovation:

- A better understanding of future investments in fast charging stations.

Reference in CINELDI:
E. Dimanchev, S.-E. Fleten, D. MacKenzie, and M. Korpås, "Accelerating electric vehicle charging investments: A real options approach to policy design", Energy Policy 181, 2023.

CINELDI result: Analysis of Flexibility Baseline Prediction Methods for Office Buildings at Different Measuring Points (WP3)

Challenge and objective:

- Customer baseline load (CBL) prediction plays an important role in calculating the volume and value of the flexibility provided by end-users.
- In this paper, two different CBL methods are applied to investigate their prediction accuracy for a given load with high resolution metered data.

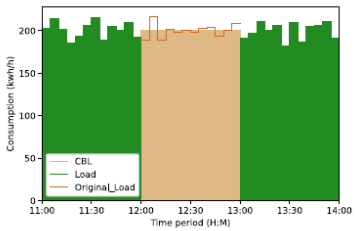


Fig. 2. Load profile measured at building-level for 11-2 PM, with CBL-calculation $CBL_{B/A}$ between 12-1 PM.

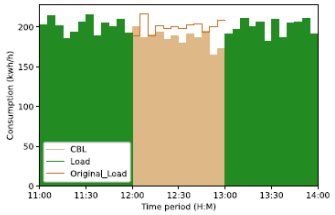


Fig. 3. Load profile measured at building-level for 11-2 PM, with CBL-calculation CBL_{XofY} between 12-1 PM.

Work performed:

- Analyzed input data at office-building level and at EV parking-lot level, compared their accuracy.
- Implemented existing CBL-calculation methods, both before/after measurements, and historical data points.

Significant results:

- Building-level measurement point performed best with use of load patterns before/after activation, due to a fixed 200-kW load import level.
- EV parking lot had much variation due to being an internal demand response for the 200-kW limit.
- Historical data was influenced by recent seasonal changed in load patterns.

Impact for distribution system innovation:

- The methods can be applied to predict the baseline load from a flexible user during flexibility activation.
- Important to be aware of internal flexible measures that could affect historical data accuracy.

Reference in CINELDI: K. E. Thorvaldsen, V. Lakshmanan, H. Sæle, "Analysis of Accuracy of Flexibility Baseline Prediction Methods for Office Building at Different Measuring Points", Conference paper, SEST 2023.

CINELDI result: Multimarket Services for Stationary Batteries Considering Activation of Frequency Reserves (WP3)

Challenge and objective:

- Wind and solar power, poses challenges related to their weather-dependent nature and the need for rotational inertia in the system. These challenges necessitate exploring new sources of flexibility to ensure stable grid operation.
- The objective of this work is to explore the viability of utilising stationary storage systems for delivering multiple services. Particular attention is given to markets for frequency reserves.

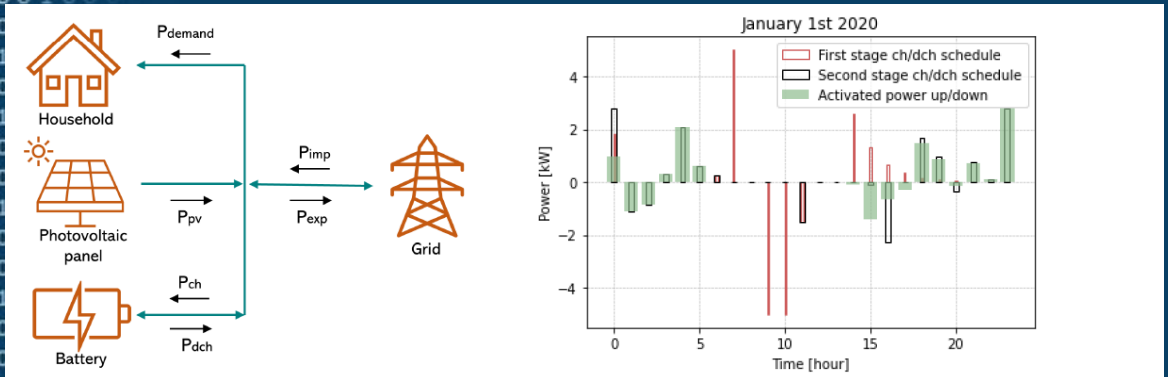


Figure 6.3.1: Change in first stage charge (ch) and discharge (dch) schedule due to activation of FCR-N reserves.

Work performed:

- Develop a scheduling model for a battery located in a household with a photovoltaic (PV) generation.
- Co-optimizing spot market and reserve market operation (The FCR-N market).
- Analysing a case study for a household in Hvaler.

Significant results:

- Providing FCR-N reserves in addition to other services resulted in declined annual expenses.
- Although the operational costs increased, the financial benefit of procuring FCR-N reserves resulted in overall decreased expenses.
- Further, the annual expenses decreased considerably after incorporating the compensation for activated energy accosted with FCR-N reserves.

Impact for distribution system innovation:

- End-users can provide multiple services with single flexible resource, at different system operating levels.

Reference in CINELDI:

- Ingvild Eline Olsen, "Multimarket Services for Stationary Batteries - Considering Activation of Frequency Containment Normal Operation Reserves", Master thesis, NTNU, 2023.

CINELDI result: Mapping of Norwegian DSOs' use of flexibility solutions for industrial grid customers (WP3)

Challenge and objective:

- DSOs require more flexible customers, as the number of connection requests is high and the lead time for constructing new grids is high.
- Flexibility from large (industrial) customers has a large potential, but it is not clear how flexibility solutions are being used during planning, normal operation and during fault situations.
- To which extent are flexibility solutions discussed as part of the dialogue between the DSO and new industrial consumers that want to connect?
- What type of industrial consumers are the most promising for being flexible?

Work performed:

- An interview study through 9 semi-structured interviews with different Norwegian DSOs.
- Mapping the DSO-customer dialogue when connecting new industrial consumers.
- Mapping the DSOs' current and planned use of flexibility solutions such as disconnectable tariffs and conditional/alternative connection agreements.

Significant results:

- There is large variation in the use of disconnectable tariffs. Some DSOs use it actively, and some not at all.
- Most DSOs have large plans for conditional connection agreements, but few have ever disconnected a customer due to the condition.

Impact for distribution system innovation:

- An increasing number of customers with conditional connection agreements leads to a need for better standardization and systems to manage more complex system operation.

Reference in CINELDI:

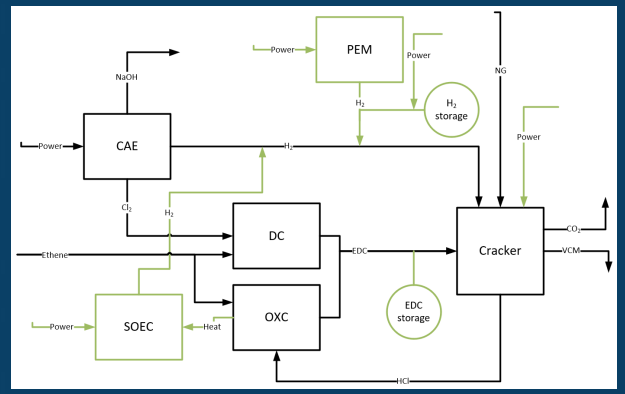
- S. Bjarghov, I. B. Sperstad, H. Sæle "Kartlegging av fleksibilitetsordninger hos næringskunder", CINELDI-report no 01:2024 (WP3), SINTEF, 2024.

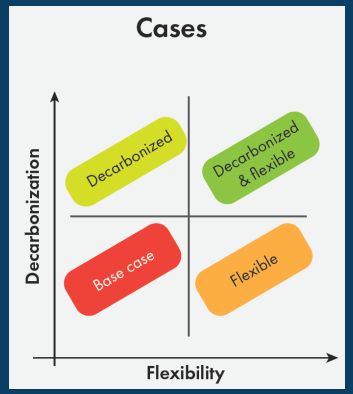
CINELDI

CINELDI result: Reducing the cost of industrial decarbonization with flexibility (WP3)

Challenge and objective:

- Decarbonization of the industrial sector is of crucial importance to meet climate goals. A significant part of the decarbonization measures are related to electrification, which will increase the strain on the power system. As industrial processes may also contribute to provide the required flexibility in the power system, this work aims to investigate the flexibility potential of a chemical industrial process, and to what degree flexibility may reduce the cost of decarbonization.





Work performed:

- An operational MILP-model is developed, representing the chemical process and its dependencies.
- The model optimizes on energy, emission and load change costs.

Significant results:

- Flexible operation of the processes is able to reduce the decarbonization cost slightly.
- There is a significant potential to reduce power demand for shorter periods of time, however, strong price incentives are required.

Impact for distribution system innovation:

- The industry sector may be exploited to a larger degree in reducing power demand in critical areas, for short periods of time. This works presents some potentials and costs for a specific industry sector.

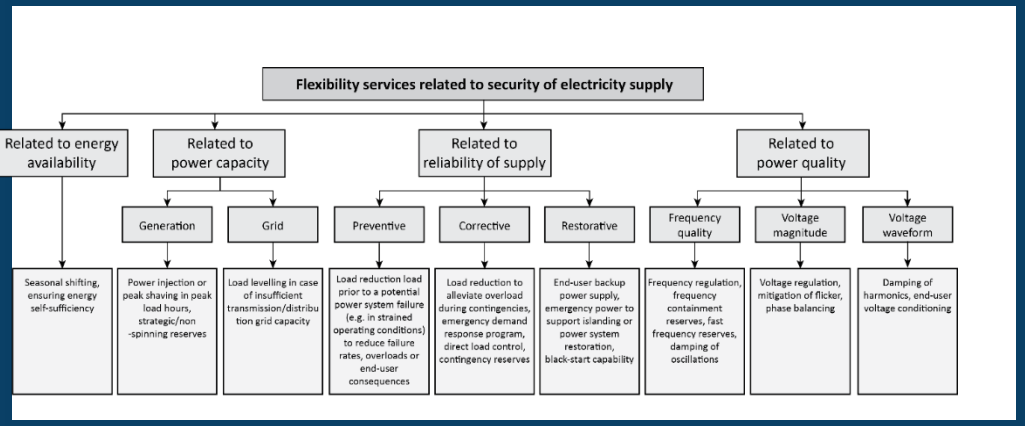
Reference in CINELDI:

- S. S. Foslie, J. Straus, B. R. Knudsen, M. Korpås, "Decarbonizing integrated chlor-alkali and vinyl chloride monomer production: Reducing the cost with industrial flexibility", Advances in Applied Energy, 2023.

CINELDI result: Review of the impact of flexibility resources in distribution systems on the security of electricity supply (WP5/WP6)

Challenge and objective:

- The power system is transitioning to a more integrated and complex system with generation and other flexibility resources also at the distribution level. This work aimed to 1) provide an understanding of how flexibility resources can impact security of electricity supply (SoS), and to 2) summarize and structure the scientific state of the art on how this impact can be quantified.



Work performed:

- Comprehensive literature review of methods and indicators for quantifying the impact of flexibility resources on SoS.

Significant results:

- Classification of flexibility services that have an impact on four main aspects of SoS: energy availability, power capacity, reliability of supply, and power quality.
- Distributed flexibility resources can have a positive impact both on a TSO, DSO, and end-user level.
- Identification of *negative* impacts on SoS and operational risks related to flexibility resources.

Impact for distribution system innovation:

- Knowledge needs and research gaps identified related to assessing security of electricity supply in future distribution systems with flexibility resources.

Reference in CINELDI:

- I. B. Sperstad, M. Z. Degefa, and G. Kjølle, "The impact of flexible resources in distribution systems on the security of electricity supply: A literature review", Electric Power Systems Research, vol. 188, p. 106532, 2020.