CINELDI Results 2020

CINELDI result: Extended vulnerability analysis framework (WP1)

Challenge and objective:

- Modern electric power systems are complex cyber-physical systems.
- The integration of traditional power and digital technologies result in interdependencies that need to be considered in risk analysis.

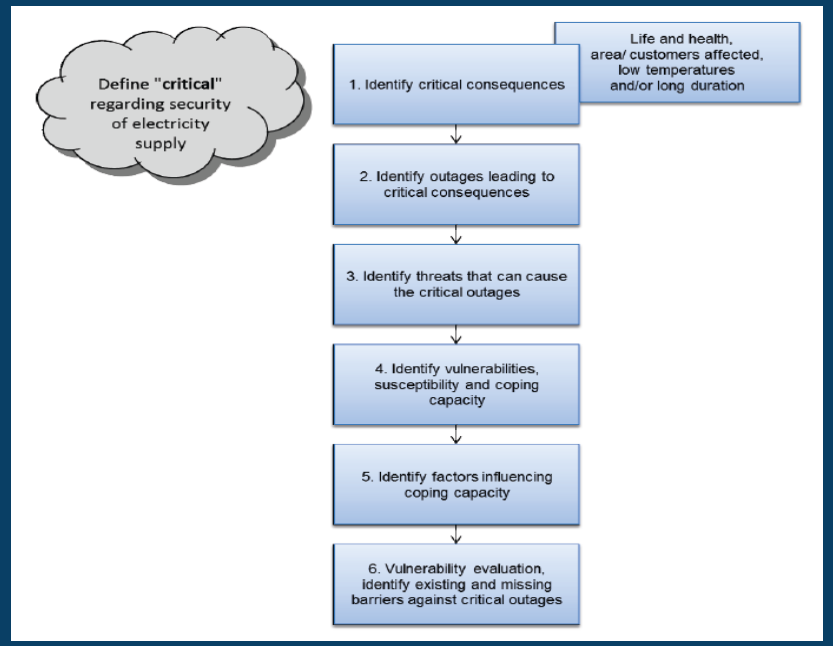


Figure source: Kjølle, Gerd H., and Gjerde, O. "Vulnerability analysis related to extraordinary events in power systems." *2015 IEEE Eindhoven PowerTech*. IEEE, 2015.

Work performed:

- The Vulnerability Framework previously developed for power systems is adapted and applied for a combined analysis of power system- and cyber security vulnerabilities on a realistic case

Significant results:

- An extended framework for combined power and ICT system vulnerability analysis, including dependencies and interdependencies
- A case study demonstrating its application, with promising results, to support further use of the framework considering interdependencies and keeping the system perspective.

Impact for distribution system innovation:

- Decision support for management of reliability of power supply affected by cybersecurity makes it possible to control vulnerability in complex cyber-physical systems .

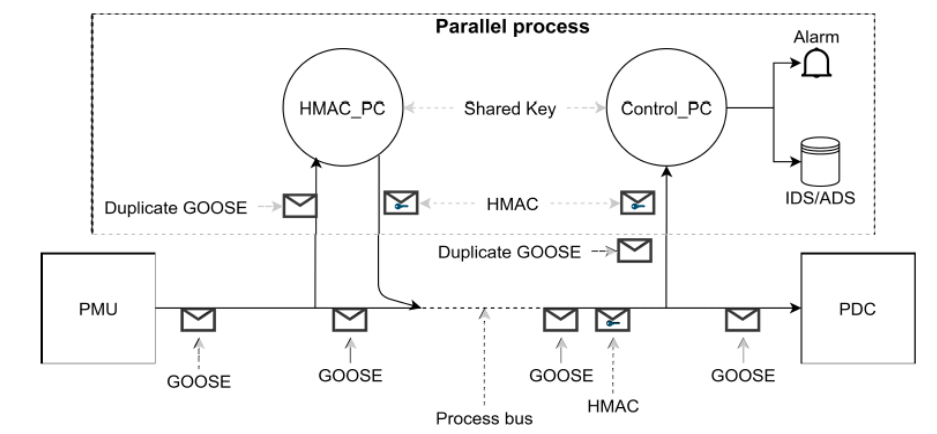
Reference in CINELDI:

- I.A. Tøndel et.al: "Hunting Dependencies: Using Bow-Tie for Combined Analysis of Power and Cyber Security", 2nd International Conference on Societal Automation - SA. IEEE, ISBN 978-1-7281-9690-9, 2021

CINELDI result: Delayed Integrity Check (WP2)

Challenge and objective:

- The state of a substation is continuously measured for monitoring, control and protection purposes, using synchrophasor measurements. The IEC 61850 standard defines communication protocols for electrical substations, including synchrophasor measurement transmission. However, IEC 61850 does not properly address cyber security, leaving this critical infrastructure highly vulnerable to cyber attacks.



Work performed:

- Developed mechanism and prototype for delayed integrity check for synchrophasor measurements. PMU traffic is sent unmodified as before, but a special device makes a local copy of each message and calculates a Hash-based Message Authentication Code (HMAC) which is sent separately. Another unit collects and checks HMAC value

Significant results:

- Developed a mechanism for delayed integrity check for synchrophasor measurements, and validated a prototype

Impact for distribution system innovation:

- Protection of synchrophasor data and other highly time-sensitive traffic.

Reference in CINELDI:

- R. Gudmestad: "Delayed Integrity Check for IEC 61850 Communication" MSc thesis at UiS, 2020
  Paper accepted at Societal Automation

CINELDI result: DSOs cooperation with vendors in handling cyber-attacks in control systems (WP2)

Challenge and objective:

- The technological evolution has enabled Norwegian Distribution System Operators (DSOs) to make greater use of products and services from external suppliers. Although outsourcing provides resources, expertise and cost-effectiveness, it also introduces new dependencies and gates for potential attacks. As the dependence upon suppliers and the system complexity increase, the use of suppliers has to be taken into account in the cybersecurity incident management for the DSOs.

Innlegg: Sviktende beredskap mot hacking i strømnettet

Små nettselskap ser ut til å være dårlig forberedt på cyberangrep mot kraftsektoren i Norge. Vellykkede cyberangrep på energisektoren er nå uunngåelige.

1 min Publisert: 19.09.20 – 15.03 Oppdatert: 6 måneder siden

Nettselskapene bruker stadig flere systemer og tjenester fra eksterne leverandører. Det skaper nye avhengigheter og øker sårbarheten ved cyberangrep. (Foto: Gunnar Blindstad)

Work performed:

- Interview study of DSOs and vendors of industrial control systems on how they cooperate on incident management.
- Current practices for the involvement of suppliers in incident management are investigated.

Significant results:

- An understanding of current practices, including both successful practices and challenges
- Recommendations for both DSOs and the power industry at large. DSOs particularly recommended to involve suppliers more in preparatory activities, and supplier contracts should be improved .

Impact for distribution system innovation:

- Awareness of the need for improved collaboration between DSOs and their vendors
- Improved cyber resilience.

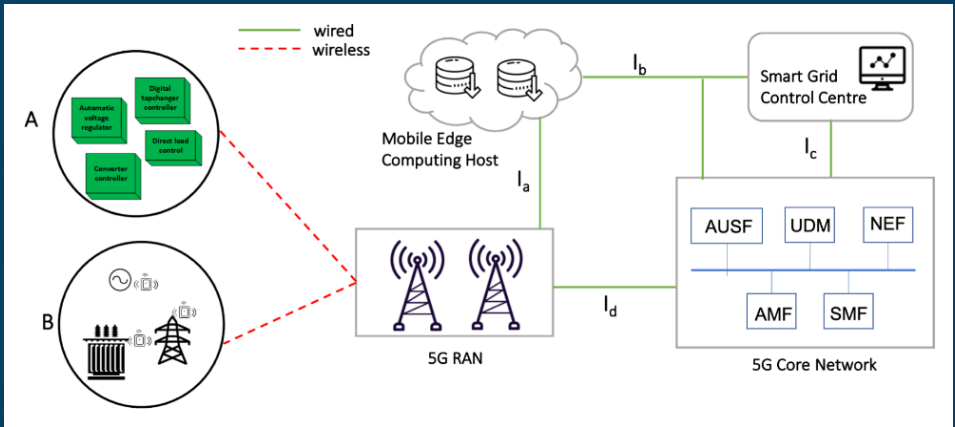
Reference in CINELDI:

- S. Waaler Eriksen and S. Gunabala: "Nettselskapers involvering av underleverandører i hendelseshåndtering ved cyberangrep" Artikkel skrevet som del av masteroppgave.
- Kronikk: https://www.dn.no/innlegg/datasikkerhet/cyberangrep/hacking/innlegg-sviktende-beredskap-mot-hacking-i-stromnettet/2-1-877303 and https://www.dn.no/innlegg/innlegg-el-norges-cyber-forsvar-trenger-leverandorene/2-1-891947

CINELDI result: Improving Smart Grid Cyber Security through 5G Enabled IoT and Edge Computing (WP2)

Challenge and objective:

- IoT and future communication networking technologies such as 5G pose security challenges to realize smart grids. The objective of study is to contribute to a better understanding of how 5G network technology can benefit security of IoT devices and communication within the smart grid.



Work performed:

- Extending voltage regulation use case as a basis for characterising IoT devices and identify key security requirements for the communication
- Threat modelling of the use-case considering massive IoT deployments with 5G wireless connectivity
- Investigation if 3GPP standardised 5G security features can address identified threats for smart grids .

Significant results:

- A smart grid use case that highlights the benefits of using 5G for secure communication with connected IoT
- A threat model of the smart grid use case that brings out important security requirements
- Overview of 5G security techniques that are applicable for smart grid domain
- Potential new threats introduced from the 5G infrastructure

Impact for distribution system innovation:

- Security analysis considering IoT and 5G based cellular communication technologies

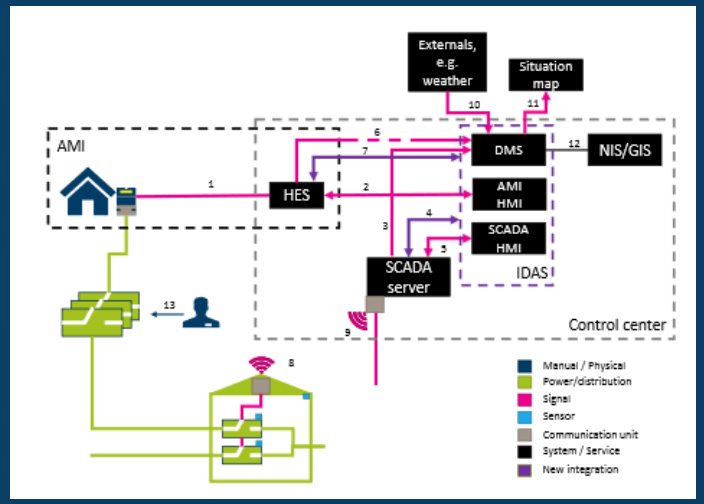
Reference in CINELDI:

- R. Borgaonkar, I.A. Tøndel, M.Z. Degefa and MG Jaatun: "Improving Smart Grid Security through 5G Enabled IoT and Edge Computing", Wiley Journal on SPECIAL ISSUE of Concurrency and Computation on SECURE MOBILE CLOUD COMPUTING

CINELDI result: Risk considerations by tighter integration of AMI/SCADA/DMS (WP2)

Challenge and objective:

- Trends indicate that Advanced Metering Infrastructure (AMI), SCADA and Distribution Management Systems (DMS) in Norway will be tighter integrated in the future, but how will this influence the cyber security risk?



Work performed:

- A workshop was organized with DSOs, vendors and NVE to to gather the stakeholders' perspectives on increased integration between AMI, SCADA and DMS, including identification of critical assets.

Significant results:

- Identified 11 threats with direct consequence for primary assets, and 22 threats to supporting assets.
- 2 of the 11 threats represent an unacceptably high risk, and 2 threats represent a medium-high risk
- Specified 13 countermeasures to the threats to primary assets

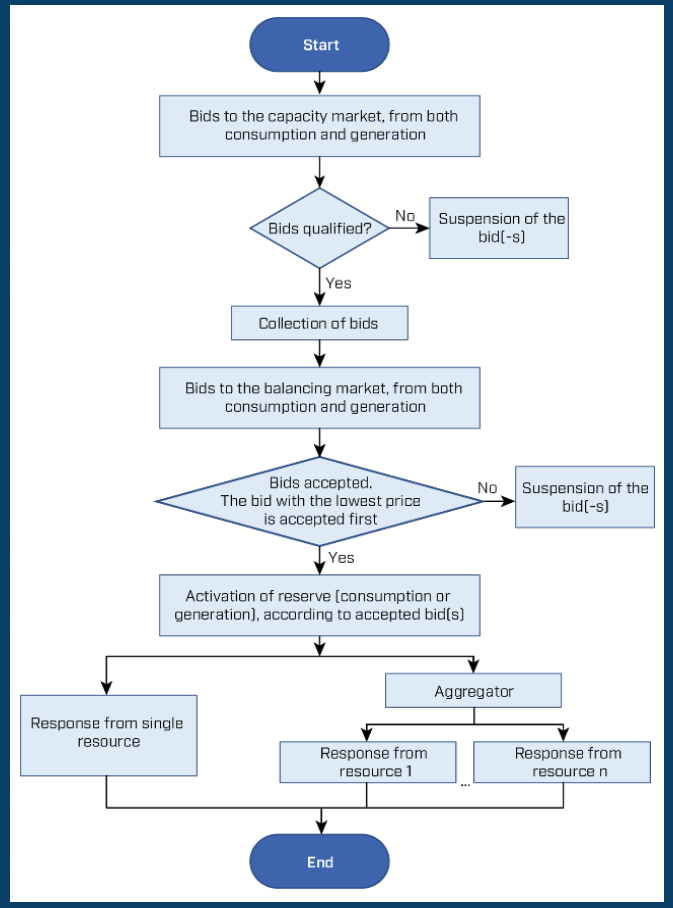
Impact for distribution system innovation:

- Risks and proposed countermeasures should be considered before implementing foreseen integration
- Proposed risk assessment methodology may be used by DSOs to perform future assessments

Reference in CINELDI:

- K. Bernsmed, M.G. Jaatun and C. Frøystad: "Is a Smarter Grid Also Riskier?" Security and Trust Management workshop (STM 2019)

CINELDI result: Use case for assessment of utilization of flexibility in ancillary services (WP3)



Challenge and objective:

- Increased need for utilization of flexibility due to digitalization, automation and more distributed generation from RES.
- Flexible resources can contribute in ancillary services on different grid levels.
- Need for coordination when several stakeholders (TSO and DSO) request flexibility services from the same resource, also to avoid new imbalances.

Work performed:

- Developed use cases describing how flexible resources can be utilized in ancillary services, such as voltage control, congestion management and balancing.

Significant results:

- A holistic approach considering technical, market and environmental aspects to evaluate utilization of flexibility resources in different ancillary services.
- Geographic location of flexible resources is important in some services (voltage control), and not services related to frequency regulation.

Impact for distribution system innovation:

- Increased utilization of flexible resources in ancillary services.

Reference in CINELDI:

- H. Sæle, A.Z. Morch, M.Z. Degefa and I. Oleinikova): "Assessment of flexibility in different ancillary services for the power system", EEM-paper, 2020
- "Use case for fremtidens systemtjenester" Webinar, Smartgridsenteret, 26. November 2020

CINELDI result: State estimation algorithm for monitoring distribution grid (WP3)

Challenge and objective:

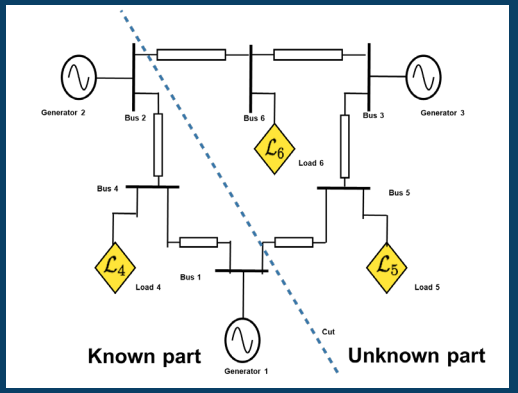
- The changes in future power grids are characterized by complexity, uncertainty and speed of changes, turning power systems into dynamical systems with dynamical characteristics.
- Difficult with state estimation in smart grids because:
  - Expensive phasor measurement units (PMUs)
  - Lack of measurements in the system due to the consumers' privacy consideration, dangerous accessibility, degradation of electrical equipment.
  - Unknown dynamical characteristics for some system components, especially for distributed generation

Work performed:

- Generated an accurate, robust and comprehensible estimate of operational state of the entire monitored power system (i.e. component's dynamics, voltages, power angles, currents, power flows).

Significant results:

- A novel modelling approach for power systems with some unknown parts, considering the whole unknown parts of a power system as system-wide unknown inputs flow into the known part.
- Developed a simultaneous input and state estimation method (SISE) to estimate the states of a partially known system with system-wide unknown inputs.



Impact for distribution system innovation:

- Prevent system-wide failures or blackouts, tune power system stabilizers, improve reliability of system models utilized for dynamic security assessment (DSA) and to design state estimator-based fault detectors.

Reference in CINELDI:

- M. Abooshahab, M. Hovd and R. Bitmead: "Disturbance and state estimation in partially known power networks", IEEE Conference on Control Technology and Applications (SINTEF Blog)
- R.R. Bitmead, M. Hovd, and M. Abooshahab: "A Kalman-filtering derivation of simultaneous input and state estimation", Automatica, 2019

CINELDI result: Coordination mechanism through high-level UC development between DSO and TSO (WP3)

Challenge and objective:

- Increased DER* connections to the distribution grid and multi-directional power flow, changing how to operate the distribution grid.
  *DER = Distributed Energy Resources, including distributed generation (DG), electricity storage and demand flexibility
- Objective to demonstrate the benefits of a coordination mechanism through high-level Use Case (UC) development between DSO and TSO.

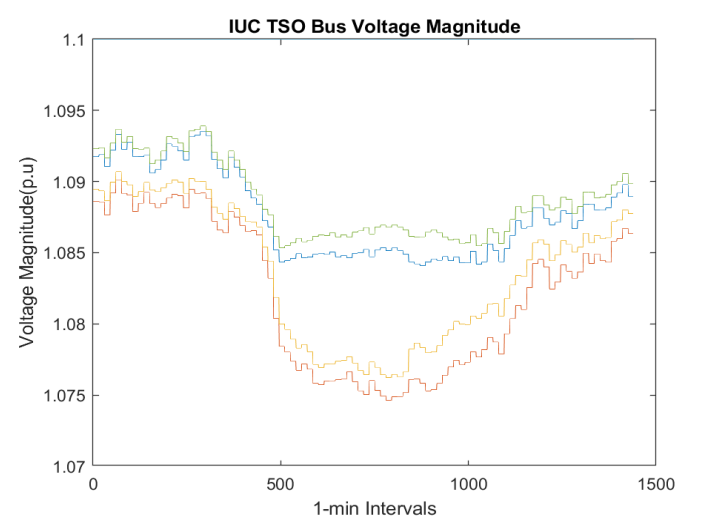


Figure: IUC TSO Bus Voltage

Work performed:

- Coordination scheme depending on an OPF tool attributing Multi-Objective (MO) optimization, considered as means resolving future operational challenges.
- Defined interoperation chain depending on sequential optimizations and exchange of relevant information and setpoints.
- Use case implemented in simulations, to manage long term voltage variations.

Significant results:

- Demonstration of benefits of TSO-DSO coordination at operational level with the fewer variable voltage profiles and closer to the required references.
- Illustration of the impact of rerouting reactive power on the total loss in the grid.

Impact for distribution system innovation:

- Operational benefits from TSO and DSO coordination in utilization of flexible resources and voltage control.

Reference in CINELDI:

- M. Farooq: "TSO - DSO Coordination for Voltage Control: Simulation Study and Use Case Development", Master thesis, NTNU, July 2020 (Webinar 2020-08-18 Benefits of TSO-DSO coordination for voltage control)

CINELDI result: Comprehensive classifications and characterizations of power system flexibility resources (WP3/5 + ModFlex)

Challenge and objective:

- Due to increased integration of renewable forms of generation, ageing grid infrastructure, and rapid increase in peak load demand, flexibility is becoming economically more viable and plays a significant role in the future power system. There is vast amount of literature on flexibility covering research, demonstration and validation activities, but there is still no unified definition of the term "flexibility" and consistent characterizing terms for "flexibility resources"

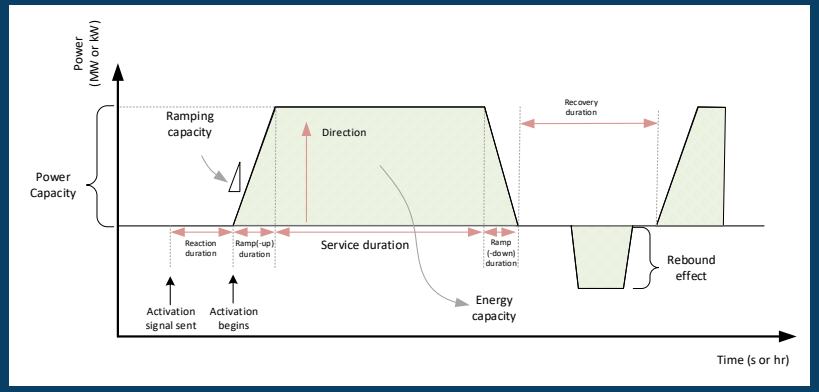


Figure: Comprehensive illustration of important characteristics of flexibility resources

Work performed:

- Review of prominent flexibility-related publications

Significant results:

- Suggested comprehensive flexibility definition and unified characterizing terms for flexibility resources.
- Suggested a taxonomy method which is applied to classify flexibility resources. The presented taxonomy method clears the confusion on "what-is-what" under the concept of flexibility.
- Presentation of unified characterizing terms in mapping flexibility resources to ancillary services.

Impact for distribution system innovation:

- Improved knowledge related to characterization of flexibility resources, that for example can be further utilized in techno-economic evaluation of flexibility resources in grid planning processes.

Reference in CINELDI:

- M.Z. Degefa, I.B. Sperstad, H. Sæle: "Comprehensive classifications and characterizations of power system flexibility resources", Electric Power System Research, 2021

CINELDI result: Definition and characterization of services to be provided by flexibility elements (WP3 + FlexPlan)

Challenge and objective:

- Flexible resources can support and/or avoid contingency situations in transmission and distribution grids, as an alternative to conventional grid extension procedures, e.g. not limited to the installation of new lines or substations.
- The FlexPlan project seeks to develop a software tool to size, locate and estimate the performance of flexibility resources to support this, and elaborate future scenarios of generation and demand.

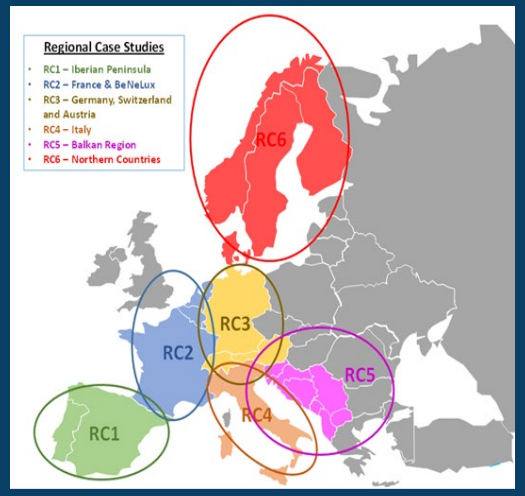


Figure: FlexPlan EU project Regional Cases (RC)

Work performed:

- Survey of ancillary services (characteristics, evolution and regional specifics at EU level), with main focus on the characterization of congestion management support services, as reference to grid planning.
- Evaluate services where storage and demand response can provide flexibility to the system.

Significant results:

- Overview of service provision requirements defining operational strategy of flexibility resources, together with their technical and economic characterization.

Impact for distribution system innovation:

- Assessment of flexibility resources from operational strategy perspective helps to define size, location, cost and performance of the flexibility resources, to be further used in system optimization.

Reference in CINELDI:

- FlexPlan D2.1: "Definition and characterization of services to be provided by flexibility elements"

CINELDI result: Guideline for the compliance of grid planning tool with EU overall strategies and regulatory conditions (WP3 + FlexPlan)

Challenge and objective:

- Changes in the Pan-European regulatory landscape, with growing share of Renewable Energy Sources (RES) as well as appearance of new loads (transport electrification, heat pump for space heating), create several challenges in distribution and transmission grids, which require compensating methods like congestion management and/or grid expansion.
- Considering use of flexible resources as a support of grid planning, has been clearly highlighted in European Directives (e.g. internal market directive of the package “Clean Energy for All Europeans”).

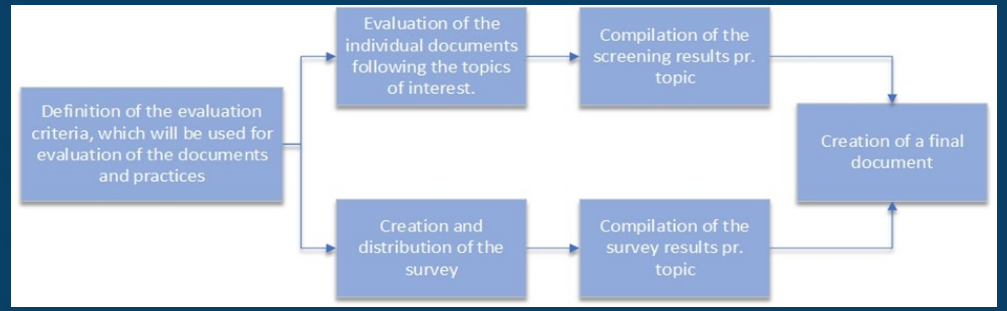


Figure: Steps in the screening methodology

Work performed:

- Assessment of the Pan-European regulatory framework through literature screening and survey-based research, further complemented by reference to existing practices at both TSO and DSO levels.

Significant results:

- Regulatory analyses carrying out an assessment of the Pan-European regulatory framework in the context of the FlexPlan project, which aims at establishing a new grid planning methodology considering the opportunity to introduce new storage and flexibility resources in electricity transmission and distribution grids as an alternative to building new grid elements.

Impact for distribution system innovation:

- Overview of Pan-European regulatory framework related to utilizing flexibility resources in grid planning.

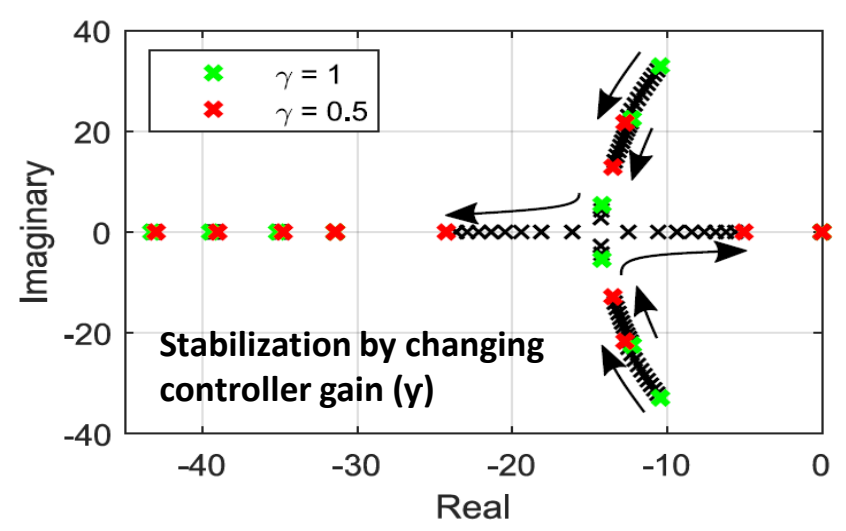
Reference in CINELDI:

- FlexPlan D6.1: "Guideline for the compliance of network planning tool with EU overall strategies and regulatory conditions"

CINELDI result: Adaptive Controller for Improved Stability (WP4)

Challenge and objective:

- Droop control commonly used for controlling microgrids (MGs) and interfacing distributed generation (DG) due to the power-sharing characteristics and low dependence on communication systems.
- The stability of MGs operated with this control paradigm is sensitive to the droop parameter values and system topology.



Work performed:

- A centralized controller for improving the stability margins of a MG is developed
- The droop gains are automatically modeled using control laws to improve the stability

Significant results:

- An automatic procedure for tuning of parameters to improve the stability in an environment with changing topologies and parameter uncertainty, enhancing the operation in the future MGs.

Impact for distribution system innovation:

- Important in the future operation where more dynamic topologies due to enhanced use of existing infrastructure and use of self-healing concepts.
- A step for a Plug & Play concept where parameters can be automatically updated to maintain stability
- The tool will enhance the security of supply.

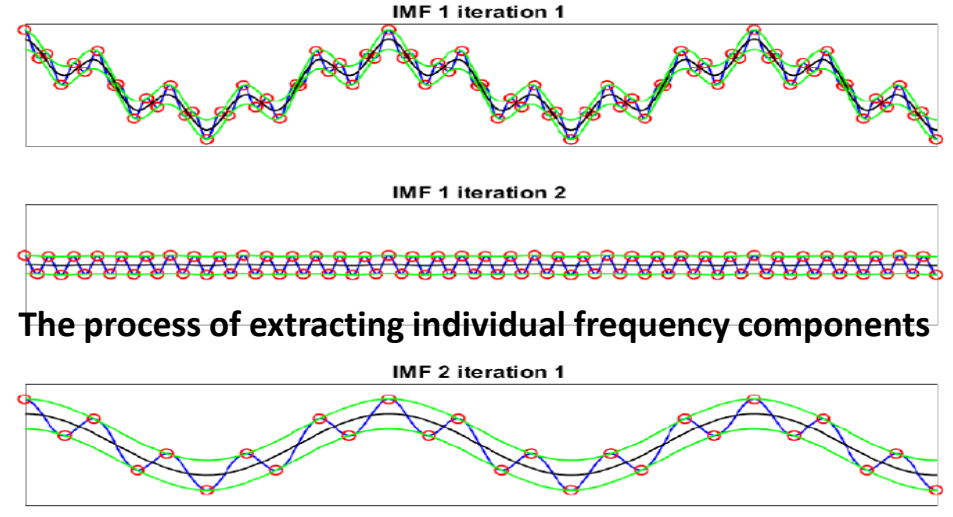
Reference in CINELDI:

- F. Göthner, R.E. Torres-Olguin, J. Roldan-Perez, A. Rygg, and O.M. Midtgård: "Apparent Impedance-Based Adaptive Controller for Improved Stability of Droop-Controlled Microgrid", IEEE Transaction of Power Electronics, 2021

CINELDI result: Instantaneous Frequency Identification in Microgrids (WP4)

Challenge and objective:

- With power electronic equipment and DG, the power system has become more prone to harmonic pollution.
- As isolated systems categorized by low inertia such as microgrids are more common, the presence of non-linear distortion is becoming an increasing problem.
- Commonly used methods for surveillance are thus not suited for the rising non-linearity caused by the harmonics, and there is a need for alternative surveillance methods.



Work performed:

- This thesis has explored the use of adaptive data analysis as an alternative surveillance method for harmonic detection in the power system.
- Empirical Mode Decomposition (EMD) and its real-time extension, Online EMD, have been used in conjunction with Hilbert-Transform (HT) and Fast Fourier Transform (FFT) for instantaneous frequency and ampl. identification.

Significant results:

- The methods proved to be powerful tools for harmonic detection when supported with techniques to handle mode mixing on more complex signals.
- The use of masking signals turned out to be a highly effective mode mixing separation technique

Impact for distribution system innovation:

- Measurement based techniques can identify special characteristics of equipment or systems when model-based techniques may fail due to parameter uncertainty
- Possible to identify the connected equipment and sources based on their response to disturbances.

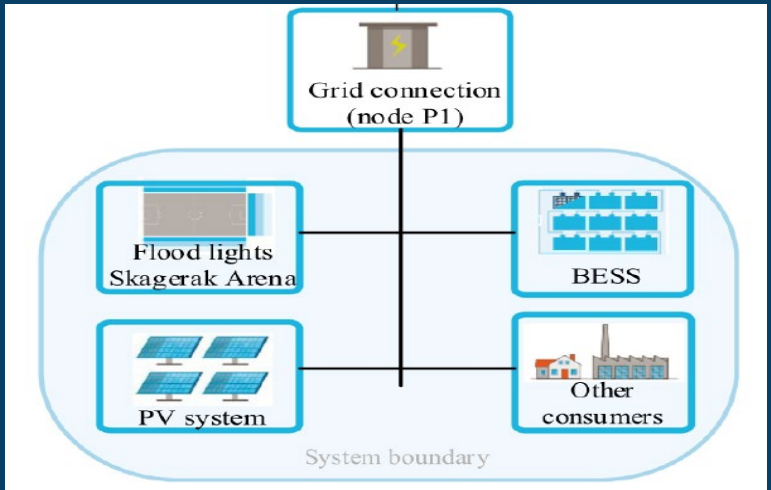
Reference in CINELDI:

- E. Westad: "Instantaneous Frequency Identification in Microgrids Through Adaptive Data Analysis", MSc-thesis, NTNU, June 2020

CINELDI result: Economic evaluation of operation strategies for battery systems (WP4)

Challenge and objective:

- Battery energy storage systems (BESSs) are making their way into the distribution grid and can typically provide services such as peak shaving, self-consumption, maximisation of photovoltaic (PV) electricity, energy arbitrage, voltage regulation, frequency control and backup power.
- Such systems can be beneficial for stakeholders at several levels, but a careful assessment is needed to design the proper combination of services.



Work performed:

- A techno-economic evaluation of case studies is performed at the Skagerak Energy Lab.
- The aim was to analyse the installation's performance by studying a variety of cases

Significant results:

- This work shows that a BESS offering stacked value by combining peak shaving, energy arbitrage, self-consumption and the replacement of a backup diesel generator, may represent a feasible option in Norway.
- The techno-economic analysis also demonstrates that the profitability is heavily dependent on the operation strategy of the BESS

Impact for distribution system innovation:

- The work describes a niche application but applicable to similar topologies or adapted to other infrastructures with backup systems.
- Improves the security of supply, reduces the peak load and may provide network ancillary services.

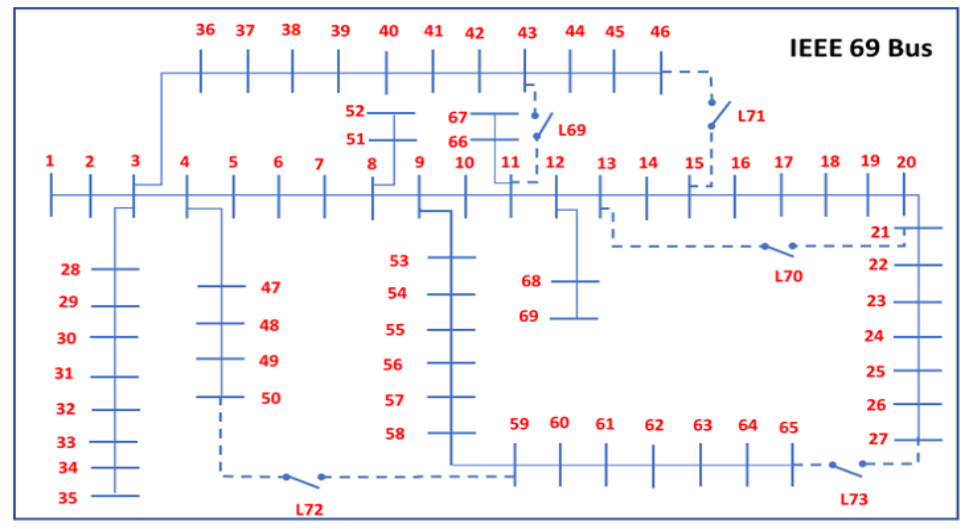
Reference in CINELDI:

- K. Berg, M. Resch, T. Weniger and S. Simonsen: "Economic evaluation of operation strategies for battery systems in football stadiums: A Norwegian case study", Journal of Energy Storage, Volume 34, February 2021

CINELDI result: Open-Source Distribution System Load Flow (WP4)

Challenge and objective:

- Robust methods are needed for decision support in distribution systems
- The tools must be able to handle flexible sources as generation, loads, storages as well as different topologies from the perspective of loss minimization and self-healing concepts
- Tools should be open-source and sufficient general to be used as building blocks in more specialized concepts



Work performed:

- A distribution system load flow is developed in Python
- It has the classical Forward-Backward-Sweep as a core but is flexible in terms of system topologies (radial operation) and provides a number of sensitivities for impact of changing active and reactive loads at individual buses
- Calculates an optimal voltage profile where both active and reactive power may be decision variables

Significant results:

- A toolbox developed which can be used by researchers in CINELDI and students as a building block for more tailor-made concepts
- Open-source available on Github
- Currently used by researchers for studying flexibility

Impact for distribution system innovation:

- The tool gives the option to quickly prototype and test special concepts
- A kernel for more advanced coordination and optimization concepts.

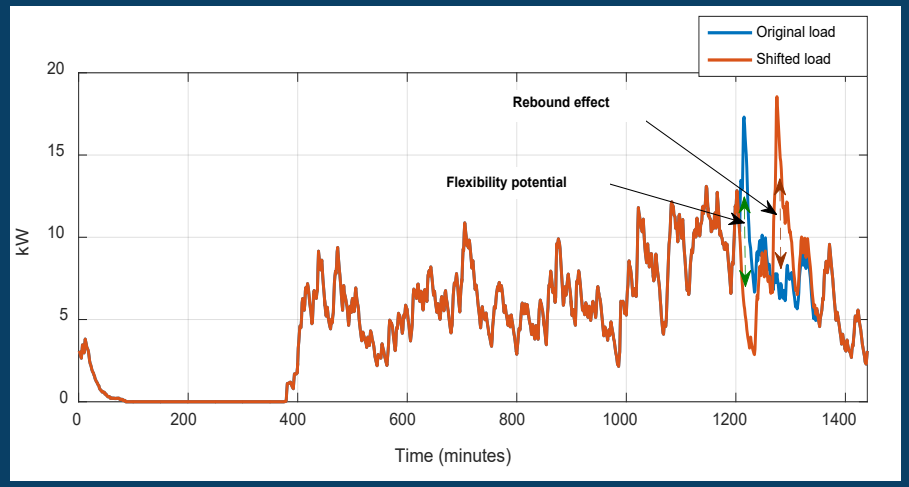
Reference in CINELDI:

- O.B. Fosso: "PyDSAL - Python Distribution System Analysis Library", PowerCon2020, IEEE Xplore, 2020

CINELDI result: Operational model for atomic loads (WP5 + ModFlex)

Challenge and objective:

- To model flexibility resources with their inherent uncertainties. Specifically modelling atomic loads, combined with customers' usage patterns for estimation of flexibility potential.



Impact of shifting cloth washing activities from hour 20:00-20:15 to hour 21:00-21:15 for average of 100 households.

Work performed:

- A flexibility modelling method for atomic loads which is based on high resolution appliance measurement data is presented. The method embraces the potential variabilities of appliance use in group of households.

Significant results:

- A method is developed which is applicable for different flexibility resources.
- A conference paper is published and the model is available through the Zenodo platform.

Impact for distribution system innovation:

- The developed method enables realistic representation of flexibility resources in the distribution grid planning. It also enables the accurate analysis of flexibility potentials and impacts of flexibility activation.

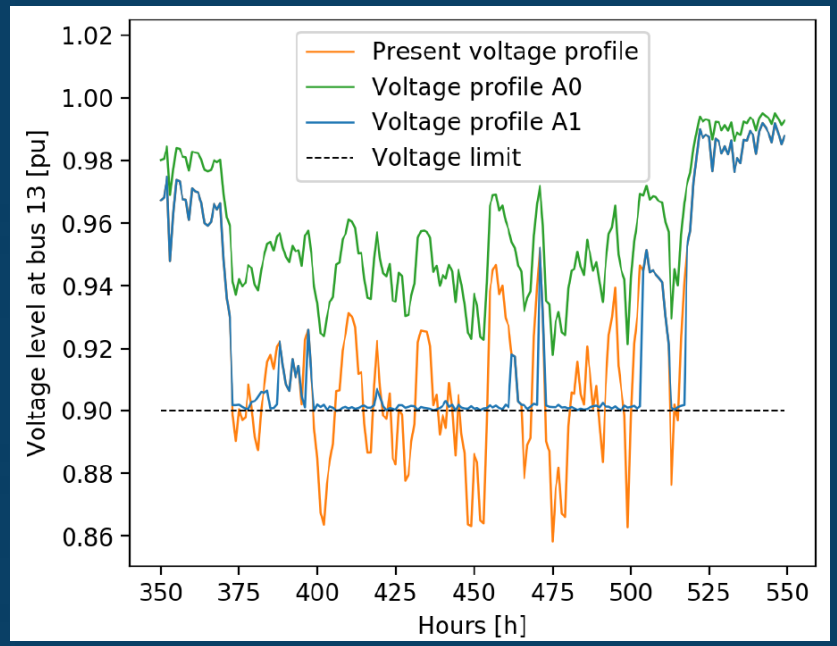
Reference in CINELDI:

- M.Z. Degefa, H. Sæle, I. Petersen and P. Ahcin: "Data-driven household load flexibility modelling: shiftable atomic load", IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe) 2018
- Zenodo: https://zenodo.org/record/3859909#.YCp4ZyRKg2w

CINELDI result: Radial power flow with battery operation (WP5)

Challenge and objective:

- Perform a techno-economic assessment of a Battery energy storage system (BESS) installation (A1) in a radial LV grid to maintain the voltage level within mandatory limits, and compare the results to traditional grid reinforcements (A0).



Work performed:

- Developed a simulation model in Python consisting of a model for running the battery as efficient as possible, a power flow solution model based on the backward/forward sweep algorithm, and an economic assessment.

Significant results:

- The battery is able to maintain the voltage level above the limit of 0.9 pu (A1 in figure) for all hours.
- The cost of installing the battery is 77 % higher than the corresponding line costs, resulting in a break-even cost of the BESS of 3900 NOK/kW and 1160 NOK/ kWh for power and energy capacity, respectively.

Impact for distribution system innovation:

- Investigate the potential for using batteries for system support as alternative to traditional grid reinforcement.

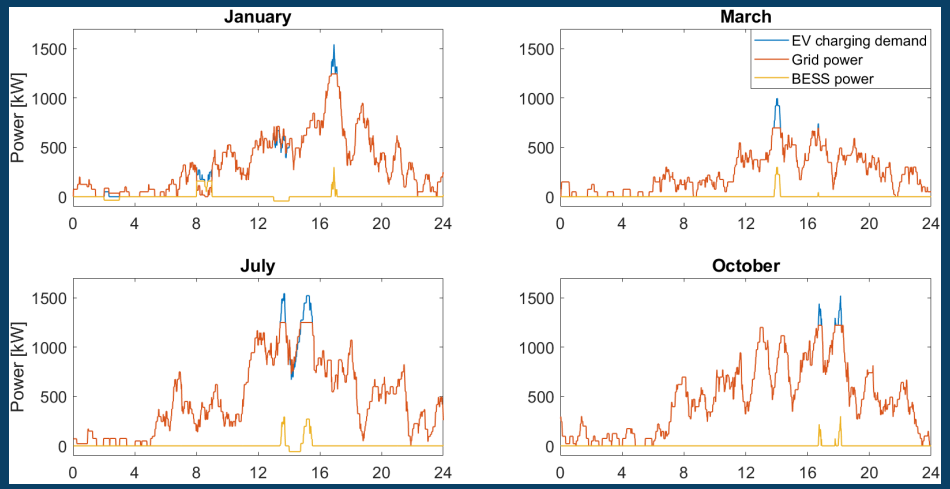
Reference in CINELDI:

- M.R. Brubæk: "Battery Storage as Alternative to Grid Reinforcement in the Low-Voltage Network", MSc thesis, NTNU, 2020

CINELDI result: Grid battery cost model with degradation(WP5)

Challenge and objective:

- Due to an increasing trend of battery application in the distribution grid, further investigation on impact from battery degradation is advantageous.
- The objective of the work is to evaluate economic impact of battery degradation by combining battery operation and degradation into one optimization model.



Daily power profiles at the EV fast charging station with a stationary BESS.

Work performed:

- Stochastic modelling of electric vehicle charging Formulation of an optimisation model for battery operation considering degradation
- Case study of a fast-charging station
- Evaluation of how time step interval, degradation and grid tariffs affect the economic assessment

Significant results:

- The battery degradation is related to investment costs rather than the operational costs.
- Higher time resolution increases the economic accuracy significantly.
- Higher power tariffs benefits battery installations.

Impact for distribution system innovation:

- Increased understanding of advantages and consequences when applying batteries in the grid.
- Proposed method to quantify economic impact from battery degradation.

Reference in CINELDI:

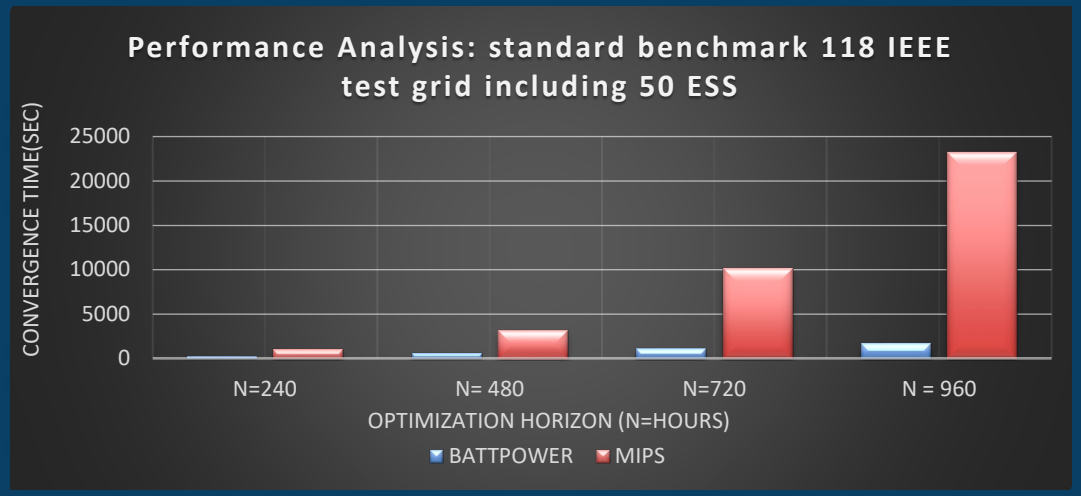
E. Haugen, M. Korpås, K. Berg: "Optimization of battery energy storage system: A case study for an electric vehicle fast-charging station", MSc thesis, 2020

E. Haugen, K. Berg, B. N. Torsæter, M. Korpås: "Optimisation model with degradation for a battery energy storage system at an EV fast charging station", IEEE Madrid PowerTech, 2021

CINELDI result: BATTPOWER: Fast computation Multi-Period OPF (WP5)

Challenge and objective:

- Large-scale integration of Distributed Energy Resources into the power systems distribution grid is crucial for reducing climate gas emisssions. To achieve this, it is of great importance for power system engineers to analyse these resources impact and operate them in a reliable, cost-efficient, and computationally tractable manner.



Work performed:

- A High-Performance Multi-Period Optimal Power Flow Solver is developed for Cost-Efficient Grid Integration of Distributed Energy Resources.

Significant results:

- Multi-Period OPF problems are solved several degree of magnitude faster than by commercial solvers when it comes to large-scale problems both with respect to time and space.

Impact for distribution system innovation:

- **Planning:** Optimising the right type, size and timing of new grid investments
- **Operation:** Optimising the use of controllable assets such as ESS and flexible demand to secure, reliable and economic operation of the distribution grids

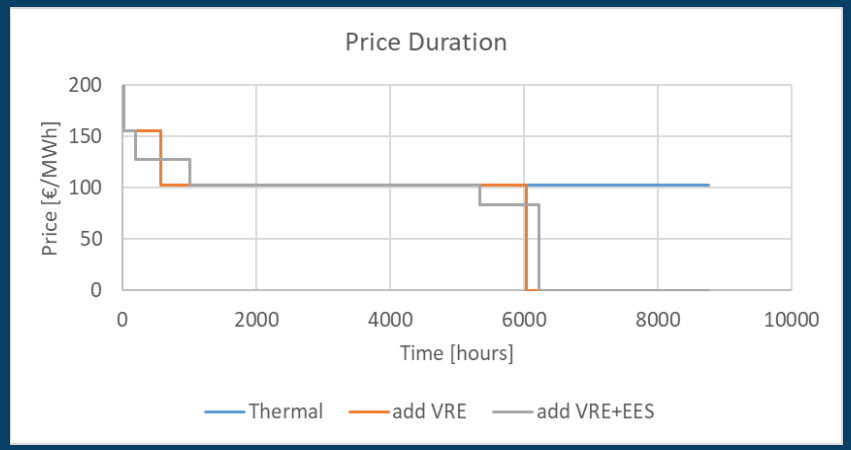
Reference in CINELDI:

- S. Zaferanlouei, H. Farahmand, V.V. Vadlamudi and M. Korpås: "BATTPOWER Toolbox: Memory-Efficient and High-Performance MultiPeriod AC Optimal Power Flow Solver", IEEE Transactions on Power Systems, 2021
- S. Zaferanlouei, V. Lakshmanan, S. Bjarghov, H. Farahmand and M. Korpås: "BATTPOWER Application: Large-Scale Integration of EVs in an Active Distribution Grid--A Norwegian Case Study", arXiv preprint arXiv:2102.02677, 2021

CINELDI result: Analytical market model for systems with renewables and storage (WP5)

Challenge and objective:

- Investments in renewables have been driven, in part, by incentive schemes and policies.
- Rapid reduction in costs for renewables and storage.
- How does these technologies influence prices and investments in competitive markets?



Example of price segments derived from the analytical model. Optimal investment in variable renewable energy (VRE) causes zero price hours, pushing thermal out of the market. Competitive electric energy storage (EES) creates new price segments based on the value of stored energy and triggers more VRE in the system.

Work performed:

- Investigate how renewable energy and electric energy storage impacts the formation of prices and optimal investments in energy-only markets.
- Develop an analytical approach to derive the system-optimal conditions for installed capacity of all generators and storage devices.

Significant results:

- All energy technologies recover their costs and maximize their profits in the system optimum, for an ideal short-term electricity market based on marginal cost and scarcity pricing subsidy schemes.
- Storage triggers more investments in renewables, replaces fossil energy and reduces CO2-emissions.
- Analytic results for how renewables and storage impact the short-term price formation under equilibrium conditions.

Impact for distribution system innovation:

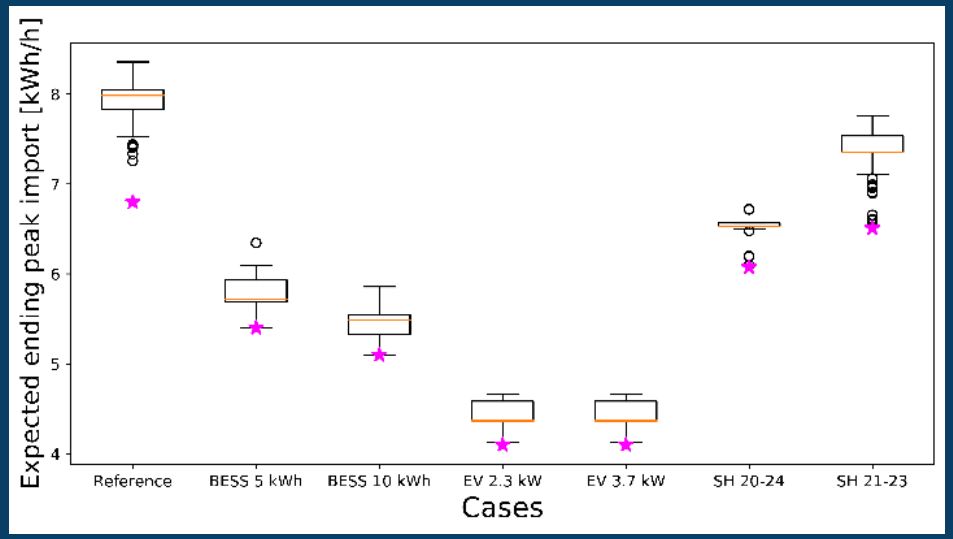
- Foundation for local market designs.
- Understanding competition in systems with storage and flexibility.
- Inputs to optimal design of microgrids in a competitive setting.

Reference in CINELDI:
M. Korpås and A. Botterud: "Optimality Conditions and Cost Recovery in Electricity Markets with Variable Renewable Energy and Energy Storage", MIT-CEEPR Working Paper 2020-005

CINELDI result: Long-term value of flexibility for building operation (WP5 + FME ZEN)

Challenge and objective:

- To represent the long-term value of flexibility of building operation
- Investigate how batteries (BESS), EV charger and space heating (SH) contribute to peak power reduction with a 1 month measured-peak grid tariff



Work performed:

- Created a Stochastic Dynamic Programming (SDP) framework for representing long-term value of flexibility of building operation
- Analyzed the SDP framework for the flexible assets individually, to see their contribution to and stability on peak power reduction

Significant results:

- Generation of future cost curves capturing the cost of increasing peak power consumption
- EV charger has the highest peak power reduction.
- Space heating contribute more on total cost-reduction than peak reduction, balancing both costs from the grid tariff and real-time pricing

Impact for distribution system innovation:

- Can give indication of value of flexibility from end-users.

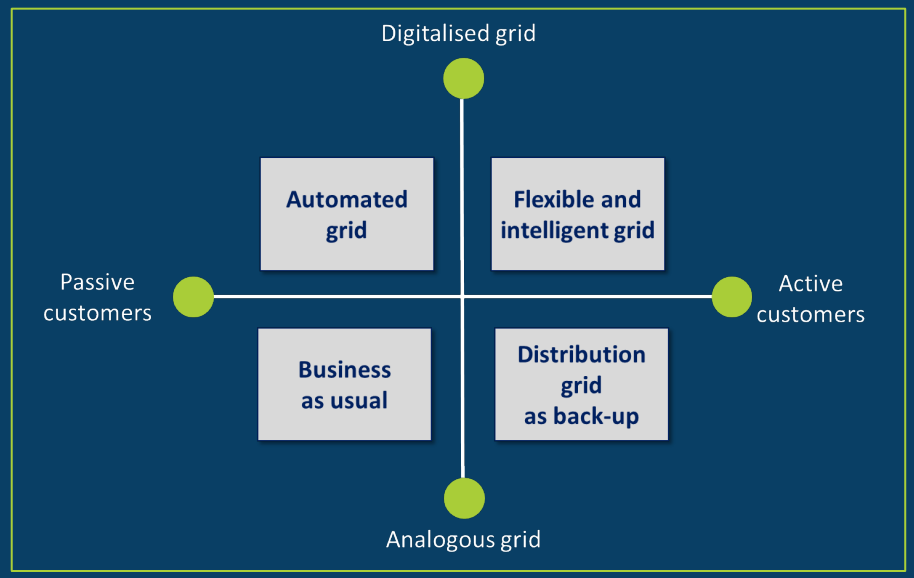
Reference in CINELDI:

- K.E. Thorvaldsen, S. Bjarghov and H. Farahmand: "Representing Long-term Impact of Residential Building Energy Management using Stochastic Dynamic Programming", International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), 2020

CINELDI result: Scenarios for the future distribution grid anno 2030-2040 (WP6)

Challenge and objective:

- Grid companies, technology providers, market operators etc. need a robust strategy for the cost-efficient transition to the future flexible, intelligent and robust grid. Driving forces and scenarios for the future grid is a useful foundation for this strategy.



Work performed:

- In 2018-2019, driving forces for intelligent electricity grid system innovation were identified and mini scenarios developed through a foresight process. Based on this, four main scenarios are established.

Significant results:

- The two dimensions *'grid customer'* and the *'grid'* stand out as the most important for the development of the future electricity grid.
- Four scenarios for the future electricity distribution grid in Norway anno 2030-2040 are described: Automated grid, Flexible and intelligent grid, Distribution grid as back-up and Business as usual.

Impact for distribution system innovation:

- The scenarios are used as a basis for research and development strategies, human resource and expertise development, developing demonstration and pilot cases, and the overall company strategies.

Reference in CINELDI:

- H.M. Vefsnmo, T.S. Hermansen, G. Kjølle and K. Sand: "Scenarios for the future electricity distribution grid anno 2030-2040", CINELDI-report no 01:2020 (in Norwegian), 2020
- G. Kjølle, K. Sand and E. Gramme: Scenarios for the future electricity distribution grid, CIRED 2021