CINELDI strategy and roadmap for transitioning to a flexible, intelligent power grid

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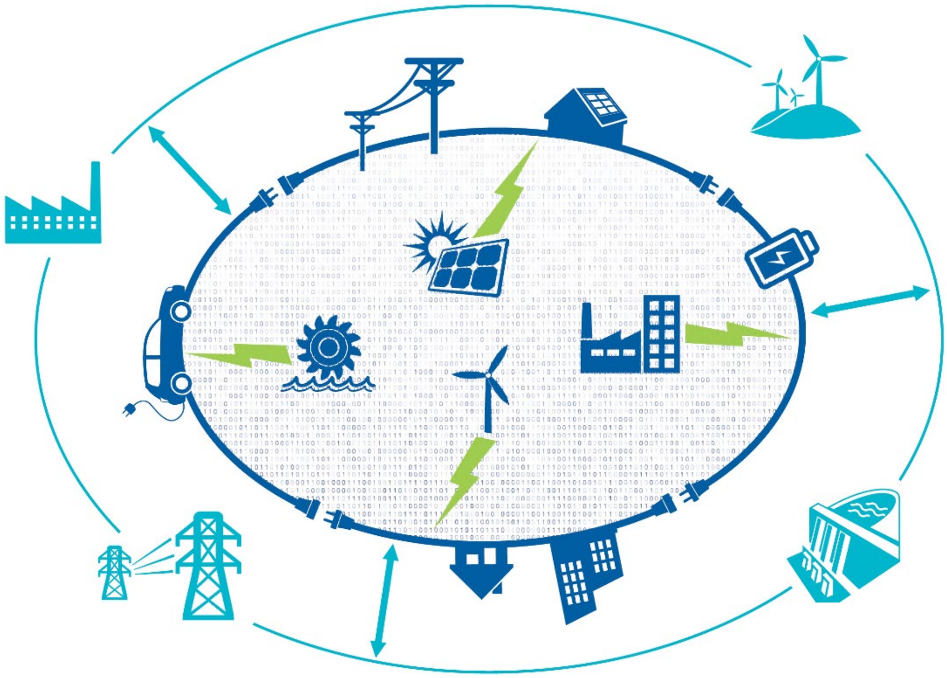

CINELDI
Centre for intelligent electricity distribution
- to empower the future Smart Grid

Centres for Environment-friendly Energy Research

CINELDI - Centre for intelligent electricity distribution

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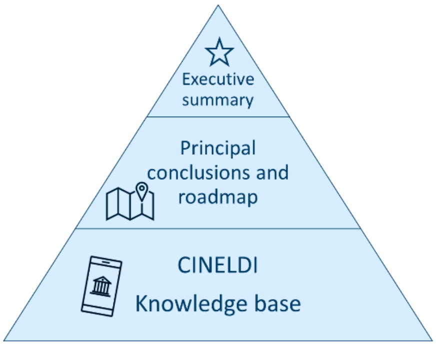
SINTEF NTNU

EXECUTIVE SUMMARY



This report summarises the results of a comprehensive strategy process in which the entire FME CINELDI consortium has been involved. CINELDI is a centre for environment-friendly energy research (FME) founded 8 years ago (2016-2024). CINELDI stands for "Centre for Intelligent Electricity Distribution" and the centre has carried on research, development and pilot projects facilitating the transition to the intelligent, flexible, robust and cost-effective electricity grid of the future, in a time of major upheaval in the energy supply system, as described in Chapters 1 and 2. CINELDI's focus is on the regional and local power grids (distribution grids) and their interaction with the national grid and system operator.

The strategy process has resulted in several recommendations, which are organised at three levels, as shown in the diagram on the left. At the bottom of the pyramid, and forming the very foundation of the strategy process, is the research and piloting carried out at CINELDI. The results of these are freely accessible in CINELDI's knowledge base[1]. This document deals with the remaining two levels of the pyramid. The strategy process has resulted in a set of principal conclusions (Chapter 3) and a roadmap for transitioning to the grid of the future in the period from 2025 to 2040 (Chapter 4). This is summarised in the Executive Summary (see next page).

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[1] https://www.sintef.no/projectweb/cineldi/cineldi-knowledge-base/

Executive summary

The Centre for Intelligent Electricity Distribution (CINELDI) is a centre for environment-friendly energy research (FME) that is developing the power grid of the future. This means an electricity grid that promotes a more sustainable society by creating conditions enabling new, renewable electricity generation, electrification of transport and other sectors, as well as more flexible utilisation of power and energy[2]. This shall be achieved at an acceptable cost while considering security of electricity supply. The power grid of the future must be flexible, intelligent and robust in order to meet the needs and challenges on the road towards the net zero-emission society. The most important results of the research and piloting carried out at CINELDI are freely accessible in CINELDI's knowledge bank[1].

The process that has led to CINELDI's transition strategy has involved many intra-consortium workshops in 2023 and 2024, as well as activity in the work packages and in CINELDI's board. The strategy process has been research-based, which means that it is founded on the research and pilot projects carried out by CINELDI. The work has led to several recommendations, organised in the form of three principal conclusions, which CINELDI believes are crucial to achieving the necessary transition of the electricity grid in the period 2025 to 2040:

1. **Widespread digitalisation and automation are necessary to gain insight into and enable control of the power grid:** To enable the optimal utilisation of the grid we must have insight into how it operates and be able to control it using active measures. This necessitates digitalisation and automation.

2. **Flexibility in the consumption, generation and storage of energy must be made use of to achieve better utilisation of the power grid.** Flexibility must be implemented to be able to connect as much consumption and new generation as possible, and to achieve better utilisation of the grid.

3. **Security of electricity supply may be compromised by extreme weather, cyber threats, increased operating loads and increased complexity of the power system, and must be handled differently in the future:** Digitalisation and flexibility provide opportunities for discovering new ways of managing security of supply.

The principal conclusions are described in detail in Chapter 3, and include, among other things, barriers and recommended actions. In conclusion, the recommended initiatives are inserted into a roadmap (Chapter 4) which describes the actions necessary to achieve the objective of an intelligent, flexible, robust and cost-effective power grid in 2040.

Achieving the objective for 2040 is a major, complex task; the key to achieving it is effective co-operation between the parties involved. We expect this will require distribution system operators, technology providers, authorities and research scientists to participate in development, adaptation, prototyping, laboratory testing and piloting. CINELDI's transition strategy forms the basis of close co-operation between all these participants in the future, among other things in spin-off projects involving research, development

[2]Ref. the objectives of the FME scheme for 2016-2024

and piloting. Examples of spin-off projects based on CINELDI's results are IPN FORSEL[3], IPN ProgLast[4], GP NextGrid[5], Pilot-E MaksGrid[6], and FME SecurEL[7].

[3]IPN FORSEL: Forced electrification by non-firm grid conditions and reliability of supply adapted to different grid customers, Innovation Project for Businesses, REN, https: //www. ren. no/artikkel/okende-elektrifisering-skaper-utfordringer (in Norwegian)
[4] IPN ProgLast: Forecasting of future demand for power and energy, Innovation Project for Businesses, Elmea, https: //www.sintef.no/prosjekter/2024/proglast/ (in Norwegian)
[5]The Green Platform initiative's NextGrid project is developing comprehensive concepts for future operation of the distribution grid, Heimdall Power, https://heimdallpower.com/heimdall-power-awarded-nextgrid-project-along-with-strong-industry-consortium/
[6]Pilot-E MaksGrid: To improve capacity utilisation and flexibility in the electricity supply system, grid utilisation will increase by 25%, Statnett, https: //www.forskningsradet.no/nyheter/2024/maksgrid-maksimal-utnyttelse-kraftnettet/
[7] SecurEL (2024-2032), a new Centre for Environment-friendly Energy Research (FME) will develop a secure, resilient and sustainable power grid, SINTEF Energi,https://www.sintef.no/siste-nytt/2024/skal-forske-pa-et-sikkert-stromnett-i-nytt-senter/ (in Norwegian)

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1 Why do we need a strategy for transitioning to the power grid of the future?

The energy supply system is in a process of major change as a result of the ambitious climate goals that Norway and Europe have defined for 2030 and 2050. The electrification of industry, transport and other sectors are among the most important initiatives for achieving these targets in Norway, Europe and globally[8,9,10,11,12]. The power grid connects consumers and power producers and is a critical requirement for electrification. The major changes in the grid will occur both locally and diversely because of solar and wind power and in more centralised form caused by new heavy load points. The existing regional and local power grid (distribution grid) is an ageing grid that is not designed to accommodate large amounts of renewable and variable solar and wind generation, or for the increasing electrification of transport and other sectors. Many of the new loads and generation sources (solar power, wind power and batteries) will be connected to the system by means of converter systems. This provides many options regarding controllability, not least in the form of independent regulation of active and reactive power. New converter concepts may also provide system services and enable island operation. New methods for increasing the utilisation of the power grid and reducing the need for investment arise from the use of new sensors, intelligent components and communication concepts that improve possibilities for monitoring and controlling the grid.

The power grid of the future will be cyber-physical and be significantly more complex, compared with the existing grid, especially in a regional and local context. Distributed generation, electrical transport, electrical energy storage, flexible grid customers and new ICT functions result in new interactions and dynamics in the use of the distribution grid, which also affects the system operation in the form of changed flow patterns and balancing requirements.

Climate and sustainability targets for the future cannot be met without changes in the power grid[11]. A new, comprehensive approach to grid development and operation is needed, while considering security of electricity supply. CINELDI has therefore developed a strategy and a roadmap for the transition to a flexible, intelligent power grid, focusing on the regional and local distribution grid and the interaction with the national transmission grid. The strategy is based on 8 years of multidisciplinary and interdisciplinary[13] research, development and innovation towards the grid of 2040, which has resulted in new know-how, technologies and concepts for the power grid of the future. These results must be implemented to facilitate the necessary changes in the power grid and to meet the needs of society regarding electrification of new types of consumption.

Public committees have reported that electrification calls for both more power generation and a more extensive grid[14,15]. Adequate grid capacity to cater for increased generation and new consumption

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[8] Electrification, IEA, 2023: available: https://www.iea.org/energy-system/electricity/electrification

[9] Net Zero Roadmap, IEA, 2023, available: https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach

[10] Climate Cure 2030 (Klimakur – in Norwegian), the Norwegian Directorate for the Environment: https://www.miljodirektoratet.no/globalassets/publikasjoner/m1625/m1625.pdf

[11] Power grids and Secure Energy Transitions, IEA, 2023: https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions

[12] Grids for Speed, Eurelectric, 2024, available: https://powersummit2024.eurelectric.org/grids-for-speed/

[13] *Multidisciplinary*: work progressing in different technical fields at the centre and *interdisciplinary*: co-operation and close interaction among technical fields.

[14] *Mer av alt — raskere* [More of everything — faster], NOU 2023: 3, Energikommisjonens rapport: https://www.regjeringen.no/contentassets/5f15fcecae3143d1bf9cade7da6afe6e/no/pdfs/nou202320230003000dddpdfs.pdf (in Norwegian)

[15] *Nett i tide*, NOU 2022: 6, *Strømnettutvalgets rapport* [Grid in time: Report of the power grid committee]: https: //www.regjeringen.no/no/dokumenter/nou-2022-6/id2918464/

patterns may be acquired both by building new grids and by improving utilisation of the existing power grid. Improved utilisation will result in more rapid grid connection and thus increased value creation in many different industrial sectors and in society. It will also result in more efficient use of the grid, which in turn will reduce the need for new building of grids, and will reduce land use, environmental damage, material use and costs.

1.1 The Energy Trilemma

Facilitating electrification and achieving climate goals without compromising the security of electricity supply must be balanced against the cost of realising the targets, as well as natural and environmental considerations. This is called the energy trilemma because the three subsidiary targets may often conflict with each other or be difficult to achieve simultaneously. In the energy trilemma the goal is to find a sound (socio-economic) balance between security of supply, cost-effectiveness and climate/environmental considerations, as illustrated in Figure 1. The following is an explanation of the energy trilemma from the perspective of CINELDI.

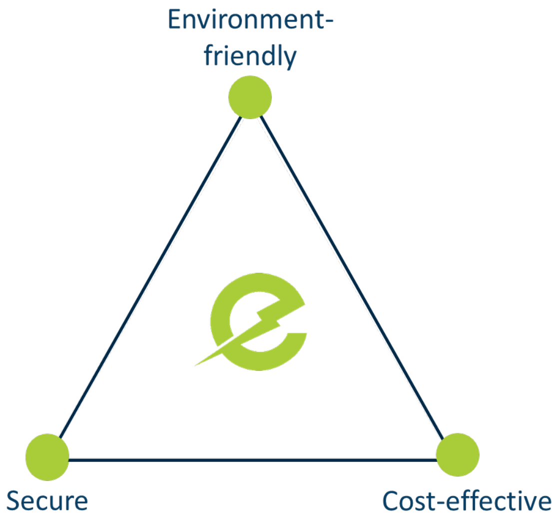


Figure 1 The Energy Trilemma.

Security of electricity supply:
CINELDI has ascertained that security of supply on the one hand may be compromised by the ongoing electrification and that digitalisation and the utilisation of flexibility on the other hand provides potential for new ways of handling security of supply in the future. Security of electricity supply comprises energy security, power security (capacity), reliability of supply and voltage quality. This also includes operational reliability, cybersecurity and personal safety. Security of supply has not been one of the principal themes of CINELDI, apart from activities connected with cybersecurity, but new issues and research needs have been identified connected with security of supply in the power grid of the future.

Cost-effective grid:
One of CINELDI's goals has been to contribute to a cost-effective realisation of the electricity grid of the future, by finding **socio-economically** optimal concepts for the grid, in line with the Norwegian Energy Act [*Energiloven*]. This means that concepts shall be found that minimise the total system costs (the sum of operating and investment costs), given the goal of a flexible, intelligent and robust power grid.

CINELDI’s research has focused on opportunities for improving the utilisation of the power grid, which will contribute to reducing the total costs.

Environmentally friendly grid:
CINELDI has contributed to national energy and climate goals on the road towards the low-emission society. This has principally involved facilitating improved distributed energy generation from renewable sources (solar, wind, hydroelectric), electrification of transport and more flexible power and energy consumption, by making better use of existing power grids and without building more new grids than necessary.

A **sustainable power grid** for the future considers the balance in the energy trilemma between security of supply, cost-effectiveness and climate/environmental considerations (See Figure 1).

1.2 Contributions to system innovation

One of CINELDI’s overriding goals has been to contribute to **system innovation** for the power grid. System innovation is defined here as a *co-evolution between technological, societal, economic and regulatory conditions.* This means that changes must take place in many factors and in several areas in parallel in order to achieve the desired changes and targets for the power grid, as defined by the energy trilemma, and various types of participants must co-operate to bring about the changes. The core participants in research and development of the power grid at CINELDI are research scientists, distribution system operators and transmission system operators, and technology suppliers. In addition, other participants, such as market operators, flexibility providers, business associations and authorities, are needed to contribute to the necessary changes.

CINELDI’s research has principally been of a technological nature, with certain elements of social science related to economics and markets, as well as end user behaviour connected with smart power grids. Although CINELDI has not carried out research into all themes involved in system innovation in the power grid, the results nevertheless provide significant contributions to the subject. CINELDI’s results are considered to provide valuable contributions to enabling the development of the other fields, such as the regulation of distribution system operators, new business models making use of flexibility, and the handling of security of supply.

2 Global analysis: Driving forces and scenarios for the power grid of the future

CINELDI has identified driving forces and established scenarios for the power grid of the future through a foresight process[16,17]. A foresight process was selected as the working method because it is highly appropriate to interdisciplinary thinking and co-operation and promotes the involvement of many different participants. This is a requirement for an FME.

An important objective for identifying driving forces is to improve understanding of what requirements are placed on the power grid of the future, as well as to develop good strategies that are also cost-effective and provide security of supply. Driving forces are grouped in megatrends, external driving forces and grid-related driving forces, as illustrated in Figure 2.

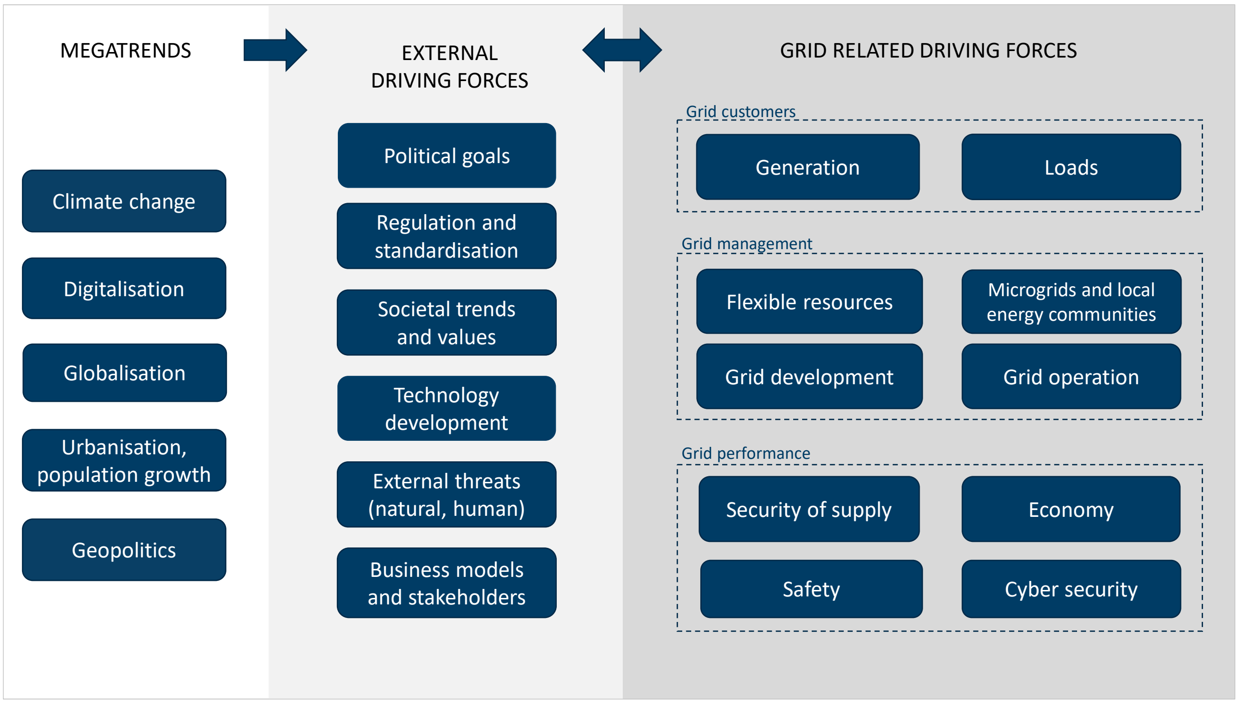


Figure 2 Overview of groups of driving forces[18].

Megatrends are global trends, while external driving forces are beyond the control of the grid operator (but can to some extent be influenced, symbolised by the two-way arrow), and grid-related driving forces are internal from the point of view of the grid operator and its relation to the grid customers[16].

Climate change, digitalisation, globalisation, urbanisation and population growth and geopolitics are global megatrends that are (highly) relevant to the grid operator and which in combination influence all the other groups of driving forces shown in Figure 2. The significance of the megatrends has changed or been reinforced during the period of CINELDI's existence[18]:

[16] Hermansen, Tonje S.; Kjølle, Gerd; Vefsnmo, Hanne; Sand, Kjell: Driving forces for intelligent electricity distribution system innovation, CINELDI-report no 01:2019 (WP6), SINTEF, 2019

[17] Vefsnmo, Hanne; Hermansen, Tonje; Kjølle, Gerd; Sand, Kjell: *Scenarier for fremtidens elektriske distribusjonsnett anno 2030-2040* [Scenarios for the future electricity distribution network from 2030 to 2040], CINELDI-report no 01:2020 (WP6), SINTEF/NTNU, 2020

[18] Kjølle, Gerd: *Drivkrefter og miniscenarier for fremtidens elektriske distribusjonsnett* [Driving forces and miniscenarios for the future electricity distribution network], CINELDI-report no 01:2022, SINTEF, 2022

- Climate change is increasing at an accelerating rate and calls for even more rapid action[19]
- Digitalisation has become a clearer trend, among other things following COVID-19
- Globalisation: Digitalisation facilitates increased globalisation and there is a growing need for international co-operation, while the aftermath of COVID-19 and conflict in Europe, (among other things) appear to have the opposite effect
- Urbanisation: There is increasing development towards smart cities, while increased digitalisation has the opposite effect because of the reduced need for physical presence
- Geopolitics: Has become increasingly important because of the energy crisis and the war in Ukraine, where energy infrastructure is under attack, both physically and digitally. This necessitates increased focus on security of supply.

Political targets resulting from climate change have resulted in electrification becoming a strong driver for grid operations. Both electrification and the megatrends affect security of supply, which is in turn a powerful driver for grid operations (as shown in Figure 2 and described in Section 3.3).

Based on identified driving forces, four principal scenarios have been established along two axes[17] (Figure 3):

- The Customer axis: The grid of the future is a consequence of the grid customers' [20] need for a grid and grid services, which in turn are determined by which apparatus, facilities, production, energy storage, control systems, etc. future customers have, as well as the behaviour of those customers.
- The Grid axis: The degree to which distribution system operators make use of new technology, new work processes and other innovations.

The Customer axis ranges from *passive customers* to *active customers*, while the Grid axis ranges from *analogous* to *digitalised* grid.

Passive customers are grid customers whose consumption and/or production/storage do not contribute to the flexibility of the power system. Active customers are grid customers whose consumption and/or production/storage contribute to the flexibility of the power system. Flexibility is here defined as: *(…) the ability and willingness to modify the production and/or consumption pattern at an individual or aggregated level, often in reaction to an external signal, so as to be able to provide a service to the power system or maintain stable grid operation*[17].

The term "power grid" here refers to the physical distribution grid, as well as work connected with planning, operation and maintenance of this grid. The Grid axis describes the degree to which new technology is made use of, compared with current standards and practice, for example in the form of new sensors, improved monitoring and automation in the regional and local distribution grid[17].

An *analogous*[21] distribution grid largely resembles the existing grid and grid operation. In an analogous grid, new technology is made use of to a limited extent and work processes (connected with operation, planning and maintenance) are to a limited extent automated. In a digitalised grid, widespread use is

[19]UN Climate report 4th April 2022: "It's 'now or never' to limit global warming to 1. 5 degrees"

[20]Grid customers include all stakeholders connected with the power supply grid: Manufacturers, end users, prosumers and energy storage operators.

[21]The term "analogous" is used in work with scenarios to represent a contrast with "digitalised" grids in which widespread digitalisation is used, in comparison with the existing grid. The "analogous" grid resembles more closely the existing grid, which also contains digital elements but to a significantly lesser extent than in a "digitalised" grid — at the other end of the Grid axis.

made of technology to enable improved observability and automation, both in the physical distribution grid and in the work processes connected with planning, operation and maintenance of the grid.

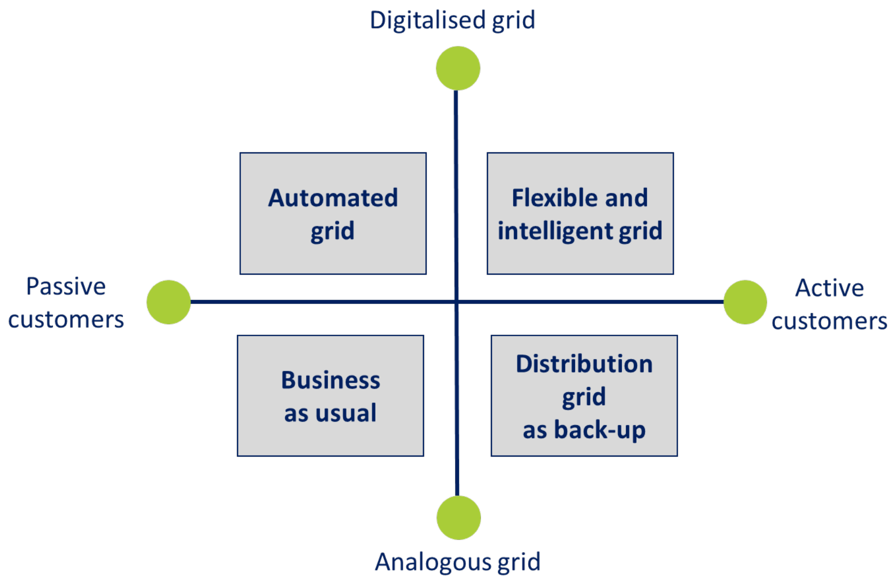


Figure 3 Scenarios for the electricity distribution grid of the future[17].

The scenario work has provided an important basis for CINELDI's research by identifying potential and challenges connected with the cost-effective realisation of the flexible, intelligent and robust distribution grids of the future. The scenarios can be used to facilitate the desired development and to counteract any undesirable developments[17]. CINELDI's aim has been that the power grid shall be flexible and intelligent (the scenario at the top right in Figure 3), and the strategy and roadmap presented in the following chapters provide recommendations for what is necessary to achieve this.

3 The principal conclusions for the transition of the power grid 2025-2040

Increased grid capacity is necessary to achieve more rapid electrification of society. This can be achieved by building new lines and by improving the utilisation of the existing grid, which in turn will reduce costs and the need for encroachment on land and the environment. CINELDI has carried out research into, developed and piloted concepts that contribute to a flexible and intelligent grid, and we have demonstrated that **improved grid utilisation can be achieved by way of digitalisation and automation of the power grid and by making use of flexible resources.**

CINELDI's principal conclusions for enabling the power grid to handle the changes necessary for a successful green transition and to meet the climate goals in 2030 and 2050 are as follows:

1. **Widespread digitalisation and automation are necessary to gain insight into and enable control of the power grid.** To enable the optimal utilisation of the grid we must have an insight into how it operates and be able to control it using active measures. This necessitates digitalisation and automation.

2. **Flexibility in the consumption, generation and storage of energy must be made use of to achieve better utilisation of the power grid.** Flexibility must be implemented to be able to connect as much consumption to new generation as possible, and to achieve better utilisation of the grid.

3. **Security of electricity supply is compromised by extreme weather, cyber threats, increased operating loads and increased complexity of the power system, and must be handled differently in the future.** Digitalisation and flexibility provide opportunities for discovering new ways of managing security of supply.

Each of the principal conclusions, with associated actions, is described in more detail in the following chapters. The actions will require close co-operation between distribution system operators, technology providers and research scientists. In addition, trade associations, aggregators, market operators, grid customers, flexibility providers and other stakeholders must participate in the collaboration. Funding providers and regulators must create the conditions necessary to achieve this co-operation.

3.1 Widespread digitalisation and automation are necessary to gain insight into and enable control of the power grid

To enable the optimal utilisation of the grid we must have an insight into how it operates and be able to control it using active measures. This necessitates digitalisation and automation.

Digitalisation and automation

The term “digitalisation and automation” here refers to various technologies and concepts for monitoring and controlling the power grid. This includes:

- Various types of sensors that provide information about the grid in a normal or fault condition.
  - Advanced measuring and control systems (AMR, smart meters)
  - Protection devices
  - Fault current indicators
  - Sensors for monitoring components (e. g., sensors for dynamic line rating)
- Communications systems necessary for transmitting information or commands
  - 5G or other wireless technologies
  - Fibre optics systems
- Manual or automatic control systems
  - Automatic tap changing
  - Self-healing functionality
  - System protection schemes
  - Control of flexible resources
  - Optimisation of topology
- Control centre systems
  - Advanced distribution management systems (ADMS)
  - Grid operation with active measures
- Other algorithms and decision support.

Active measures in the grid

Active measures in the grid differ from passive measures such as grid expansion, reinforcement and re-investment. Active measures in the grid entail the use of resources that are either directly or indirectly under the control of the control centre. Examples are switching, voltage regulation, self-healing functionality and the use of dynamic load limits.

According to Statnett[22], annual consumption in Norway is expected to increase from 140 to 220 TWh between now and 2050, and power generation will in the long run need to be increased accordingly. The need for electrification is driving this increase, requiring distribution system operators to build a lot of new power lines at all grid levels so that the new power generation and consumption can be connected. Statnett plans to invest NOK 100-150 billion in the grid over the next ten years[23], and the distribution system operators are planning investments totalling NOK 14.5 billion in regional and local grids in 2024

[22] Long-term market analysis, Statnett (2023)

[23] Statnett. (2023). *Systemutviklingsplan 2023* [System development plan 2023]. Statnett. https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/planer-og-analyser/sup/systemutviklingsplan-2023.pdf

alone[24]. According to DNV, global demand for grid capacity will increase by a factor of 2.5 and annual investment needs will more than double by 2050[25].

Grid expansion can be a slow process, and it is important to make maximum use of the existing grid to provide as many grid connections as possible, as quickly as possible. Similarly, we want to make the best possible use of the new power grid that is being built, to achieve more cost-effective solutions and reduce land use and environmental impact. With the help of innovative initiatives made possible by digitalisation and automation solutions, this can be done without compromising security of electricity supply[26] (see Fact Box, Section 3.3). These measures are referred to as risk-based grid planning, operation and maintenance, and involve the distribution system operator taking a known risk that is within the limits that the company and society consider acceptable.

The connection of new, distributed and weather-dependent renewable generation, together with large amounts of new load, significantly increases the complexity of the power grid. At the same time, the power grid must be operated closer to its limits. This requires a better overview and more control, so that operators get good decision-making support and, in turn, the necessary basis for automating time- and operation-critical functions and measures.

The necessary technology, including sensors and communication systems, is largely already available. CINELDI's research and piloting has confirmed that based on more detailed information, the transmission capacity of power lines can be increased for large parts of the time, while there may also be periods when capacity cannot be increased or should be reduced. CINELDI has also shown that today's technology makes it possible to get a good overview of voltage conditions, power flow, grid topology and fault situations as a basis for decisions and automation of grid operations. New algorithms have been developed that can help to efficiently detect and locate faults, and methods and algorithms have been developed and tested that make it possible to operate the grid in new ways so that fewer customers lose power in the event of a fault, as well as for self-healing grids[27] that minimise the duration of power outages and restore supply automatically. It has also been shown that digital inspection can provide opportunities to streamline information gathering and optimise the maintenance of the power grid. Digitalisation enables data collection, processing and prediction, as a basis for decision support for planning, operation and maintenance. In the future it is expected that new methods, including methods based on artificial intelligence (AI), can supplement and streamline several of these applications.

To be of practical use, the information from all sources needs to be included in the distribution system operators' systems and presented in appropriate ways, so that operators and grid developers can use it as decision support or as input data for automated systems. Furthermore, increased complexity and cybersecurity related to the management systems must be addressed already in the planning phase.

[24] Europower. (2023). *Boom i nettselskapene: Investerer mer enn noen gang* [Boom for the distribution system operators: Investing more than ever]. Europower. https: //www. europower. no/nett/boom-i-nettselskapene-investerer-mer-enn-noen-gang/2-1-1589617

[25] DNV New Power Systems (2024), https://www.dnv.com/publications/new-power-systems-report/

[26] Security of electricity supply: The power supply system's ability to continuously deliver electricity of a given quality to end users. https://energifaktanorge.no/norsk-energiforsyning/forsyningssikkerhet

[27] Self-healing grid functionality: technology and processes for automatic fault location and isolation, and automatic restoration of power supply to intact parts of the distribution grid.

<table>
<tr><td colspan="3">Principal Conclusion 1:
Widespread digitalisation and automation are necessary to gain insight into and enable control of the power grid: To enable the optimal utilisation of the grid we must have an insight into how it operates and be able to control it using active measures. This necessitates digitalisation and automation.</td></tr>
<tr><th>Potential</th><th>Reasoning</th><th>Barriers</th></tr>
<tr><td>With a good overview and management, the utilisation of the grid can be increased without the risk becoming too high.

Much of the necessary technology, including sensors, for decision support and automation is already available, enabling a rapid response from the control centre in the event of a fault.

Fully automated grid operations with actions based on digital twin predictions is a vision for the future.</td><td>Rapid and increased connection of more distributed and variable generation and new loads requires that grid development be supplemented by active grid operation, and today's grid planning and grid operation methods must be adapted accordingly.

Data-based grid planning and automated, data-based operations are needed to maximise grid utilisation.</td><td>Increased digitalisation and automation necessitate system integration that in many cases does not exist today. Increased complexity and uncertainty related to cybersecurity management can slow down this integration.

Changes in grid operation and increased grid utilisation as a result of digitalisation and automation will change the risk picture.

The distribution system operators cannot handle this alone, and co-operation between different stakeholders is necessary to achieve the goals.

The distribution system operators lack incentives, methods and tools for calculating and communicating risk.</td></tr>
<tr><th colspan="3">Measures</th></tr>
<tr><td colspan="3">Instrument, standardise and collect data: Data quality and the availability of data in the right channels (and sharing between tools and stakeholders) are prerequisites for utilising CINELDI’s results. Existing and new grids must be instrumented, the collection of (high-resolution) measurements must be established, data quality must be specified, data formats must be standardised, and data exchange and interoperability must be facilitated. Digitalisation and automation systems must be specified and standardised.

Further develop decision support tools, demonstrate and pilot future active grid operation: Further develop and implement solutions for dynamic line rating for important connections, develop and test automatic voltage regulation, functionality for self-healing grids (in defined grid areas), automated</td></tr>
</table>

decision support for connections, and automated grid operation. Methods that are not yet ready to be tested in real grids or operations can be tested in the laboratory, e. g., in the National Smart Grid Laboratory[28] at NTNU.

Develop and deploy operational tools for risk analysis and visualisation: Based on experience from demos and pilot projects, tools can be developed in ordinary use for risk analysis and risk visualisation in connection with grid operation. Data-driven methods and artificial intelligence (AI) can be relevant, together with more traditional methods and tools, for analysing data, mapping and analysing risks and visualising the results. In order to develop and use the necessary tools, it is necessary to train relevant expertise, particularly in the fields of ICT and risk analyses in the power system.

Develop and introduce automated grid operation: The introduction of automated grid operation is a general goal in a power grid characterised by rapid and large variations, high complexity and many alternative actions. This will be made possible based on experience from pilots and demos, where the new methods are tested over time by providing decision support for operators' actions and automation of individual initiatives and automation in defined grid areas.

Further develop and pilot new methodology for grid planning: Data-based (AMR and other sources) and stochastic load modelling methodology, and planning methodology using both active and passive measures, must be further developed and tested.

Develop and introduce risk-based planning methodology at full scale: Based on experience from piloting and testing risk-based planning methodology, a natural aim is to develop the tools required to introduce this at full scale in the organisation. Here too, it may be relevant to consider AI as a method, e. g., for automatic generation of alternatives and visualisation.

Further develop and implement new methods for asset management: CINELDI and collaborative projects have developed methods for smart asset management that show the connection between component condition and reliability of supply. These methods should be further developed and implemented in collaboration between distribution system operators, technology providers and research scientists.

Introduce data-based asset management at full scale: Based on the experience gained from piloting and testing data-based asset management, a natural aim is to develop the tools required and introduce this at full scale in the organisation.

Disseminate results, share knowledge and best practices for tools throughout the industry: Trade associations/companies and meeting places for distribution system operators must be actively used to share experiences and establish best practices, so that the development of new key tools and processes for the operators is collaborative and leads to increased standardisation in the industry.

Adapt regulations to the need for rapid connection and increased grid utilisation: It is important to ensure that regulations and incentives always facilitate the fastest possible connection of new production and loads and provide the best possible balance between increased grid utilisation and grid development.

[28] The National Smart Grid Laboratory: https://www.ntnu.edu/smartgrid/the-national-smart-grid-laboratory

Pilot projects on digitalisation and automation of the power grid[29]**:**

- Machine learning in grid inspection
- Digital Inspection[30]
- Smart Cable Guard
- Flexible power grid by dynamic operation
- Added value from Smart meters
- Predicting peak load in secondary substations
- Data Driven Failure Risk Assessment for Predicting maintenance
- Detection of earth faults based on data from smart meters
- Creation and use of management data in 3D in the field
- Condition-based maintenance of substations
- New protection concept
- Fault indicators and self-healing
- An algorithm for self-healing
- Fault indicators
- AGI - Artificial Grid Intelligence for detecting earth faults in MV distribution grids
- Automated protection and outcome analysis for dynamic grid operation
- Production Plans available for the Control Centre.

Innovation stories

"Flexible power grid by dynamic operation" is CINELDI's largest pilot project, whose participants are technology suppliers, distribution system operators and research partners. Such collaborations are essential because they ensure progress and dissemination of the results of pilots. In this pilot, the facility of many sensors at multiple grid levels supports the principal conclusion: "Widespread digitalisation and automation is needed to provide an insight into, and control of the power grid". The sensors provide information about, among other things, temperature and current in transmission lines. This is important for determining true capacity and making precise predictions about future capacity. The goal is to operate transmission lines with dynamic capacity limits, approaching their actual capacity. Such predictions must be available in the operational control systems in order to be used in the operation of the power grid. Integration with operational control systems is therefore an important activity together with innovation arising from the pilot project. It is also important that different distribution system operators (DSOs) and the transmission system operator (TSO) exchange information so that they can acquire a better overview and make better decisions with the help of data from outside their own grids. DSOs and TSOs have been working on this in collaboration, but the final solution for data exchange for dynamic capacity is not in place.

Furthermore, the pilots "Added value from Smart meters", "Detection of earth faults based on data from smart meters" and "AGI - Artificial Grid Intelligence for detecting earth faults in MV distribution grids" have worked on the efficient detection and handling of earth faults. Every year, distribution system operators spend large sums on detection, customer contact and other measures to eliminate earth faults, so these pilots have potential for considerable savings for the operators.

[29] Pilot projects at CINELDI: https://www.sintef.no/projectweb/cineldi/pilot-projects-in-cineldi/
[30] There are three different pilot projects under Digital Inspection: https://www.sintef.no/projectweb/cineldi/pilot-projects-in-cineldi/

3.2 Flexibility in the consumption, generation and storage of energy must be made use of to achieve better utilisation of the power grid.

Flexibility must be implemented to be able to connect as much consumption and new generation as possible, and to achieve better utilisation of the grid.

Flexibility and flexible resources[18]

Flexibility is defined as the ability and willingness to modify the production and/or consumption pattern at an individual or aggregated level, often in reaction to an external signal, to be able to provide a service to the power system or maintain stable grid operation.

Flexible resources are production and/or consumption resources, and/or energy storage, where injected or consumed power can be modified at an individual or aggregated level, by agreement with the distribution system operator and/or a third party (e. g., an aggregator) so that they are included in and can benefit system operation.

Increased consumption and more weather-dependent production create a need for the use of flexibility and flexible resources in the power system (see Fact Box). This is important because:

1. A lot of new lines must be constructed, but in many cases, this does not happen quickly enough. Flexibility increases the degree of utilisation of the power grid we already have, so that the grid has less of a braking effect on the green transition.

2. The use of flexibility and active measures (see the Fact Box in Section 3.1) in the grid are important tools in the grid planning process in addition to passive measures (grid development), and can be used to reduce the risk of operational challenges pending the construction of new lines. It can also contribute to more socio-economically appropriate investments.

3. With a greater proportion of weather-dependent (non-controllable) production, we need to utilise flexibility so that the load more closely follows production, in order to balance consumption and production in the power system. In this way, problems with voltage, frequency and thermal limitations in the grid can be avoided.

This means that the use of flexible resources is necessary both in the current situation with limited grid capacity, and after the grid has been expanded. CINELDI's research and piloting has shown how flexible resources can be understood, classified and modelled, as well as how the use of the flexible resources and active measures affect the grid. It has been demonstrated how a combination of flexibility and active and traditional measures (grid development) in the grid can be used to plan active distribution grids. This has subsequently been used to show when the best possible time to invest is, and how flexible resources and active measures can be used to manage the risk of operational challenges. Most of CINELDI's research has focused on consumer flexibility in buildings and households, batteries and electric car charging.

Even though flexibility can meet challenges in both grid planning and operation, it is not being used extensively in Norway today. It has been recognised that new work processes, agreements, market concepts and standardisation are important prerequisites for the large-scale use of flexibility[22]. In order to ensure that flexibility is utilised in the power system, the value chain for flexibility needs to be viewed from a holistic perspective. This value chain is shown in Figure 4 and includes grid customers who can contribute flexibility, grid operators (DSO/TSO) who want to buy flexibility, stakeholders and technology for realising and activating flexibility, and a regulatory framework that facilitates the application of flexibility. Business models are needed that apply to the entire value chain and ensure profitability for all stakeholders involved (see Figure 4). In addition, digitalisation and automation are needed (see Principal Conclusion 1).

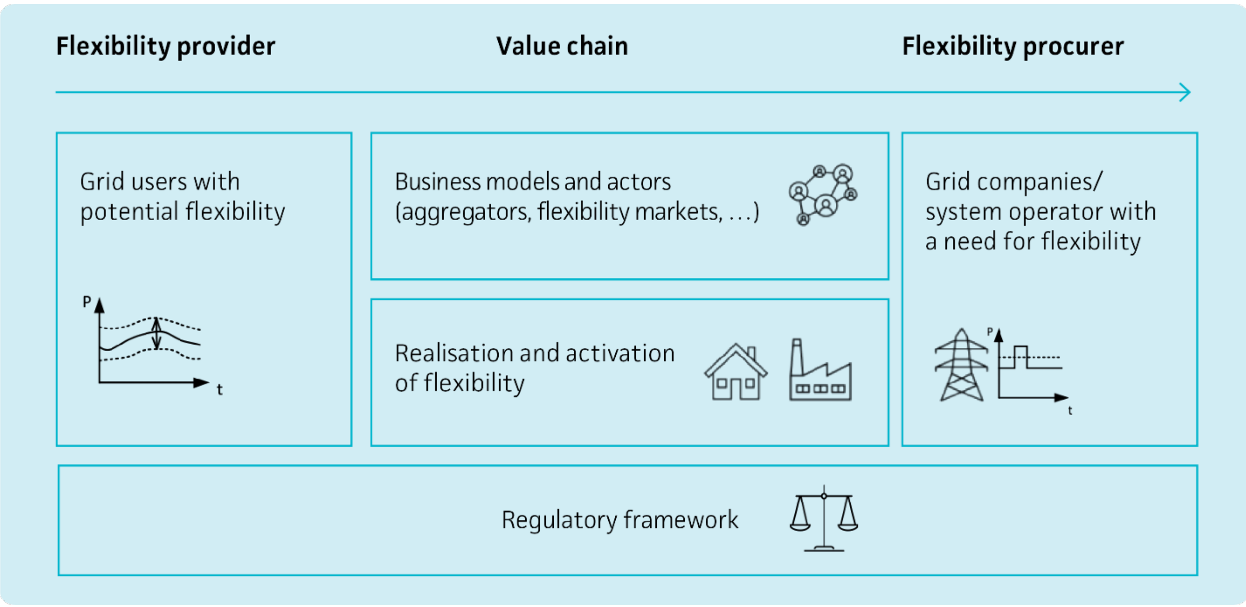


Figure 4 Value chain for flexibility.

Principal Conclusion 2:		
Flexibility in the consumption, generation and storage of energy must be made use of to achieve better utilisation of the power grid: Flexibility must be implemented to be able to connect as much consumption and new generation as possible, and to achieve better utilisation of the grid.		
Potential	**Reasoning**	**Barriers**
Flexible resources increase the utilisation of existing power grids, so that new consumption can be connected while waiting for the grid to be expanded. This assumes that flexibility and active measures are included in the grid planning process to help build the right amount of grid at the right time and control risk during the lead time. At the same time, an increasing share of non-controllable production will result in a growing need for flexibility to balance the power system. Flexible resources can improve system stability and help avoid operational challenges such as congestions and voltage issues. Flexibility can also be helpful during critical operational situations. Realistic modelling of flexibility in the grid planning process in conjunction with the use of flexibility in the operational phase can contribute to fewer outages and of shorter duration. Aggregation of flexible resources through aggregators can provide greater potential to interact in a co-ordinated way with the needs of the grid.	On the road to a renewable society, with an increased share of power generation based on solar and wind, and reduced emissions through electrification (for example, of transport and industry), there is a need for rapid connection of new consumption and more renewable production to the electricity grid. This requires increased grid hosting capacity, but it can take a long time to build new grids. Better utilisation of the electricity grid helps to optimise the use of resources, both in terms of the infrastructure itself, and in terms of areas expropriated, and the impact on nature. This reduces the need for encroachment on land and the environment, and at the same time makes the distribution system operators' operations more cost-effective. Flexibility and active measures in the grid should become natural tools in connection with grid planning because they help to postpone grid investments in anticipation of better information about load development, and because they can be used to control operational risk until grid reinforcement is in place.	Current work processes and tools used by the distribution system operators are not sufficiently organised for planning and operation with flexibility. In addition, there are challenges related to a lack of observability between neighbouring and overlapping grids, as well as the mapping and activation of flexibility. There are few standardised flexibility products for the distribution grid, and the value of flexibility is not well enough established. By making use of flexibility, more participants will be involved, which will change the current picture of stakeholders, and their tasks related to the planning and operation of the power grid. Customer acceptance of sharing personal data (about electricity use) with third parties. Lack of profitability resulting from the use of flexibility. Lack of marketplaces/solutions for the use of flexibility. Cyber risks associated with the activation of flexible resources can jeopardise security of supply.

To ensure the best possible benefit for the power system, market solutions and agreements/contracts must be optimised based on the purpose for which the flexibility is to be used, and by whom.		Flexibility in planning must go hand in hand with flexibility in operation: An overview is needed of which active initiatives are fixed in the planning process, and which are available during operation.
Measures		
Further develop methods for mapping available grid capacity, both in the short and the long term: If distribution system operators are to utilise flexibility and other active measures, they first need to know what the demand is, both over the year and in an operational planning perspective (the next 48 hours). Load forecasting and modelling, and the use of sensors to map available grid capacity, are important elements in knowing where it will be necessary to use flexible resources to solve problems in the grid. **Develop and introduce standardised flexibility products:** It will be necessary to standardise the agreements that make customer flexibility available to distribution system operators. This can be achieved by defining a limited set of flexibility products and developing standard flexibility service agreements for different areas of application. **Further develop tools that show available flexibility:** The distribution system operator needs an overview of available flexibility in terms of type, size and location. It will be necessary to further develop existing prototypes that illustrate the benefits and consequences of alternative choices. **Pilot the use of flexibility for active grid operation:** Distribution system operators are participating in pilots and increasingly using flexibility for active grid operation and to manage bottlenecks, for example, rather than using traditional approaches. The pilot projects should emphasise standardisation and the development of scalable solutions that can be used in other applications than those where they have been tested/piloted. **Establish a system for co-ordinated use of flexibility across grid levels:** If the use of flexibility is to be optimised regarding adjacent and overlapping grids, it must be co-ordinated between DSO-DSO and DSO-TSO. It is necessary to define a systematic approach or framework for how this should be done. **Implement methodology in tools to optimise flexibility use across grid levels:** Once a methodology for flexibility co-ordination is in place, it must be implemented in the relevant operational tools so that co-ordinated flexibility utilisation takes place in practice. As part of the optimisation methodology, a risk-based approach should be used to determine where purchasing flexibility will offer the solution. **Develop models for the value of flexibility and verification of delivered flexibility:** Research should be carried out on the role of flexibility in maintaining security of supply, the value of flexibility and verification of delivered flexibility. **The flexibility models should then be implemented in grid operation tools.** **Develop business models for flexibility:** Ensures profitability for all stakeholders in the flexibility value chain. **Further develop marketplaces for trading between DSO, aggregator and customer.**		

Implement tools that automatically interact with flexible resources: In the long term, flexibility trading and activation can be automated from the control centre.

Investigate the societal and social consequences of utilising flexibility in the power system (continuous): If connection agreements and regulations are to move in the direction of load management becoming more common, research should be conducted on the social acceptance of these changes to ensure that the power system does not increase social discrimination.

Introduce regulations that facilitate power co-ordination, production sharing and activation of flexibility: For example, power co-ordination and production sharing among end users in local energy communities, and development of incentives to activate flexibility in strained grid areas (beyond "connection with terms and conditions").

Implement a new standard connection agreement that makes customers' flexibility available: Distribution system operators should move away from today's standard connection agreements and establish a new standard that makes it easier to utilise existing flexibility in the grid — also for existing customers.

Pilot projects on flexibility and flexible resources in the power grid[31]:

- Flexible power grid by dynamic operation
- Risk-based distribution network planning
- Probabilistic planning methodology
- Development area Molobyen
- Batteries as voltage support
- NODES flexibility platform
- Flexibility market
- Optimisation of local balancing with battery
- Utsira: An islanded grid on an island
- Transition to and from island mode
- Active homes
- iFleks
- Fast Frequency Reserve
- System for use of flexible resources
- Transmission and Distribution coordination via Hierarchical clearing.

Innovation stories:

The "Risk-based distribution network planning" and "Probabilistic planning methodology" pilot projects have tested alternative methods for grid planning. The former has tested various methods and assessed the advantages and disadvantages of the different methods, which is important for further selection of methods and future choice of software. The latter resulted in an openly accessible code platform and an open dataset of industry loads. Both the code and the dataset are important for further work in more probabilistic and risk-based planning and have been important for CINELDI's research work.

The "Active Homes" and "iFleks" pilot projects show that there is potential to realise flexibility among end users, but that it is challenging to communicate with end users, because they are such an inhomogeneous group. The pilot projects provide important input regarding how communication should take place. These two pilot projects are the only activities that deal with implicit flexibility* at CINELDI and thus have involved end users directly in the pilot activity.

The "System for use of flexible resources" pilot project involves distribution system operators and software suppliers. Here, a more efficient system has been created and tested to obtain an overview of and, if necessary, disconnect/reduce load for customers with disconnectable tariffs. The aim of this is to be able to utilise already available (but little-used) flexibility in the planning and operation of the grid. New software has been developed and, given that customers with disconnectable tariffs are located in areas with a need for flexibility, the benefit for the distribution system operator can be high.

The two pilot projects "NODES flexibility platform" and "Flexibility market" have tested a platform for trading flexibility on the island of Utsira and in Bremanger. Technically, this has worked well, but the challenges have been to find enough flexibility providers and to determine the right price for the flexibility. Work is continuing to address these challenges. NODES flexibility platform** is in use at present at many localities in Norway and Europe, with more than 12,000 flexible resources available.

* Implicit flexibility is flexibility that is made available through price signals.
** (https: //nodesmarket. com/nodes-platform/).

[31] Pilot projects at CINELDI: https://www.sintef.no/projectweb/cineldi/pilot-projects-in-cineldi/

3.3 Security of electricity supply is compromised by extreme weather, cyber threats, increased operating loads and increased complexity of the power system, and must be handled differently in the future.

Digitalisation and flexibility provide opportunities for discovering new ways of managing security of electricity supply.

The Norwegian Water Resources and Energy Directorate (NVE) defines *security of electricity supply* as the power system's ability to continuously deliver electrical power of a given quality to the end user[32]. It consists of four main elements:

- *Energy security:* access to enough energy to produce electricity
- *Power security (capacity):* access to capacity to satisfy the power requirement at all times
- *Voltage quality:* the quality of the voltage supplied to the end user
- *Reliability of supply:* availability of electrical energy, related to the number of outages and duration of outages.

It also includes *operational reliability*, which is the power system's ability to withstand disruptions without exceeding specified limits, and *cybersecurity*.
Security of electricity supply is also affected by interactions between these elements.

At the present time, the security of electricity supply in Norway is very high[32,33]: Reliability of supply is at around 99.98%, which means that Norwegian end users on average experience outages for 2-3 hours per year. Thanks to CINELDI's research into electrification, digitalisation and flexibility, it has become increasingly clear that changes are coming that will affect security of supply. The energy trilemma has come into the spotlight as the emphasis on climate and the environment has increased, and not least with the energy crisis in Europe in the wake of Russia's attack on Ukraine, where security of supply has come higher up on the agenda. We must avoid a situation where security of supply considerations delays important societal goals in the fields of electrification and climate. CINELDI has identified new issues and research needs related to security of supply in the electricity grid of the future, and initial research has been conducted on cybersecurity and its impact on security of supply. In addition, a study has been carried out of how flexible resources can affect security of supply, and methods have been developed and principles discussed for the automatic restoration of supply after faults in the grid (self-healing functionality).

A power grid with a high level of security of supply, which is robust and resilient, is crucial for the green transition and increased sustainable value creation in society. The electrification of society is highlighted as one of the most important initiatives to reduce greenhouse gas emissions and achieve the goal of a net zero-emission society in 2050. The digitalisation of the power grid and the use of flexibility are leading to increased utilisation of the grid and faster electrification, but this can impair security of supply and change the risk picture, among other things through an increased likelihood of exceeding system limits, reduced margins and increased complexity. Greater variation in power production and consumption will place greater stress on the grid and components, the risk of component failure may increase, and lifetimes may be reduced. New renewable power generation is connected using transformers, and transformer technology can provide improved opportunities for control, but power

[32]*Driften av kraftsystemet 2023* [The operation of the energy supply system 2023], https://publikasjoner.nve.no/rme_rapport/2024/rme_rapport2024_04.pdf

[33]*Hvor sårbart er vårt elektriske energisystem?* [How vulnerable is our electricity supply system?]SINTEF og NTNU, Arendalsuka 2022, https://www.sintef.no/globalassets/sintef-energi/arendalsuka/2022/forsyningssikkerhet_lr.pdf

electronics can also pose stability challenges in the grid. Today's static system limits are conservative, and there is a need to develop new concepts for monitoring and risk management of the grid that make it possible to establish more dynamic limits to increase grid utilisation. It is necessary to obtain an overview of the actual risk to maintain control. This will potentially facilitate risk-based planning, operation and maintenance of the grid.

Security of electricity supply is challenged by increased operational stresses, increased weather-related stresses and more extreme weather, and by cyber threats. New vulnerabilities arise as a result of the digitalisation of the power grid and the development towards a cyber-physical system, increasing complexity and society becoming more dependent on electricity. It is therefore important to understand how security of electricity supply and the resilience of the cyber-physical power grid are affected by large-scale electrification, new threats and vulnerabilities, and how it can be maintained on the road to a net zero-emission society. In order to handle higher grid utilisation, greater use of digitalised and automated solutions, and the use of flexibility, new knowledge is needed about security of supply in the future. This also includes the need for improved knowledge of new ways of managing security of supply using new technology and flexibility, and of how this can be perceived as fair and accepted in society. It will also require new methods and work processes for managing security of supply in day-to-day grid operations with new roles and responsibilities among system operators, and in interaction with grid customers (power producers, end users and flexibility providers).

Principal Conclusion 3: **Security of electricity supply is compromised by extreme weather, cyber threats, increased operating loads and increased complexity of the power system, and must be handled differently in the future:** Digitalisation and flexibility provide opportunities for discovering new ways of managing security of supply.		
Potential	**Reasoning**	**Barriers**
If the green transition is to be successful, security of electricity supply must be safeguarded. New technology and flexibility can provide opportunities for new ways of managing security of supply in the future. It is possible to safeguard security of supply and achieve control of risks associated with the changes taking place in the environment and surrounding world in terms of climate/weather stresses, in the development of the cyber-physical system and as a result of electrification. This will potentially facilitate risk-based planning, operation and maintenance of the grid. Potential for more socio-economically sound security of supply in the electricity grid of the future, and more appropriate total socio-economic costs (the sum of investment, operation and maintenance, outage and loss costs).	Security of supply must be balanced against the cost of realising climate goals and consideration for nature and the environment. We currently lack knowledge of the consequences for security of supply of the changes in the power system as a result of electrification, increased weather stresses, digitalisation and increased complexity. A robust and resilient power grid is necessary, and we need to take advantage of new opportunities offered by new technology (digitalisation and automation) and flexibility to manage security of supply in new ways. This also calls for new know-how.	Lack of data and indicators to determine the actual condition of components and systems and associated risks related to security of supply. Lack of definitions and models for how risk can be measured and quantified. Lack of opportunities to differentiate security of supply beyond non-firm connections. Social acceptance of increasing risk and/or reducing security of supply. System functionality related to self-healing grid functionality, and new protections etc. for fault management, are not sufficiently established. Lack of observability and co-ordination between TSO and DSO for security of supply and clarification of roles among different stakeholders (including end users themselves) to manage security of supply.
Measures		
Define risk-based criteria and principles and establish a risk-based approach at all levels of the distribution system operator: The risk-based approach to grid planning, operation and maintenance will only work if it is established at all levels of a distribution system operator. If the grid is planned according to risk-based criteria, the operating environment must recognise this. For the grid to be operated with a risk-based approach, this must be with the commitment of the distribution system operator's management. **Further develop and test risk-based methods and criteria:** Develop risk understanding,		

indicators and methods, test risk-based grid operation on digital twins and compare with actual (ordinary) operation, pilot risk-based grid operation in specific parts of the grid, but build new grid where demand requires it.

Introduce risk-based planning, operation and maintenance of the power grid: The risk-based approach is important in all core processes of a distribution system operator. When risk-based methods and criteria are established, it facilitates risk-based planning, operation and maintenance.

Further develop and implement tools for mapping cyber risk: CINELDI has developed a method for mapping cyber risk in the grid planning phase and assessing how this affects security of supply. The method should be adopted and expanded to apply to all core processes of a distribution system operator, including operations and maintenance.

Map and elucidate interdependencies between energy carriers, domains and grid levels: The power grid is evolving into a cyber-physical system and becoming more closely integrated with other energy carriers and sectors. It is important to map and understand the interdependencies and emerging threats and vulnerabilities that arise. Energy carriers can be, for example, electricity, hydrogen, or district heating, and examples of domains are cybersecurity and ICT.

Develop a methodology for managing resilience: Resilience is the opposite of vulnerability and is becoming increasingly important in a power system and grid that are changing and exposed to new stresses, e. g., as a result of increased utilisation of the grid. Resilience is part of security of supply, but there is a lack of methods and tools to deal with this, for example as part of supply reliability and restoration of supply.

Build the knowledge base for differentiation of security of supply: Establish the necessary knowledge and methods, establish principles for security of supply, roles and societal acceptance. Long-term competence-building research (research centres for environmentally friendly energy (FMEs) and competence-building projects for industry) to acquire new knowledge of the status, risks and new ways of managing security of supply, and of valuation and social acceptance related to, for example, differentiation of security of supply.

Use digitalisation and flexibility to manage and differentiate security of supply: Make use of new opportunities (new technology, digitalisation, flexibility and microgrids and/or local energy communities (LECs)) for managing and differentiating security of supply. Generate knowledge of societal acceptance.

Define responsibilities and roles in the value chain, between grid levels (TSO/DSO) and end users.

Pilot and introduce new principles for managing security of supply: Use pilots as a learning arena to manage security of supply, reduce barriers, contribute to innovation and standardisation, for example, piloting local energy communities interacting with the distribution grid (in terms of grid support services, security of supply, financial incentives, etc.), households and industrial energy communities.

4 Roadmap for the power grid of the future (2025 – 2040)

The roadmap is divided into the three themes that make up the principal conclusions:

1. Widespread digitalisation and automation are necessary to gain insight into and enable control of the power grid (Principal Conclusion 1)

2. Flexibility in the consumption, generation and storage of energy must be made use of to achieve better utilisation of the power grid (Principal Conclusion 2)

3. Security of electricity supply is compromised by extreme weather, cyber threats, increased operating loads and increased complexity of the power system, and must be handled differently in the future (Principal Conclusion 3)

Short-term (2025-2030) and longer-term (2030-2040) measures are proposed under each principal conclusion. The measures that can be implemented in the short term are results from CINELDI and/or existing methods or technology that can be used directly, possibly with some (further) development or piloting. In the longer term, the measures that can be implemented are methods or technology that are not yet ready for use or where there is a lack of knowledge, and where more research and development are needed first. A common target for the power grid in 2040 is described in the far-right column. This explains what will be achieved if the measures are implemented.

Common to all the measures is that TSO, DSOs, technology suppliers, research scientists and others must work more closely together to shorten the path between research, piloting, innovation and established best practice.

Table 1 Roadmap for Principal Conclusion 1: Widespread digitalisation and automation are necessary to gain insight into and enable control of the power grid.

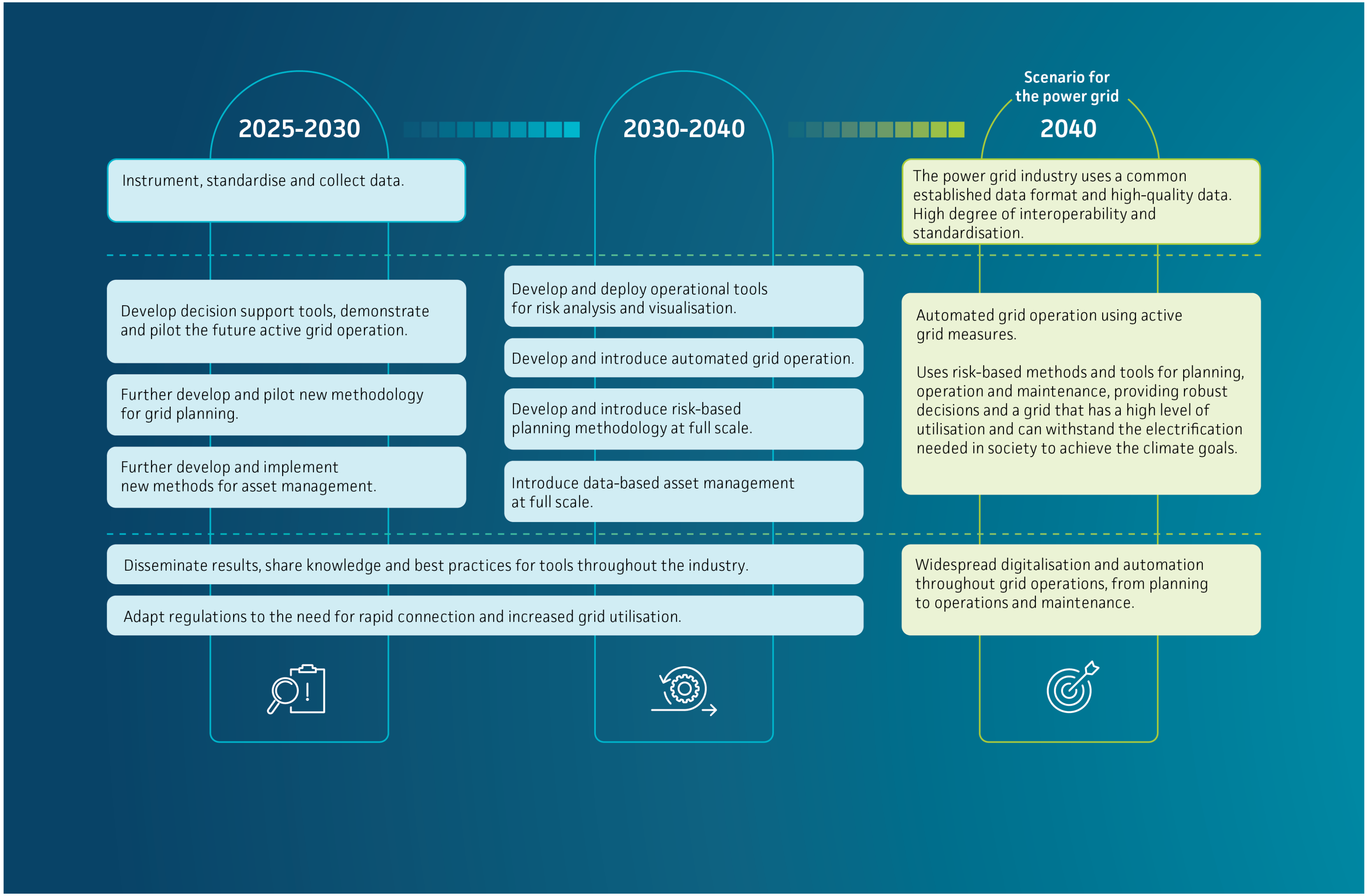
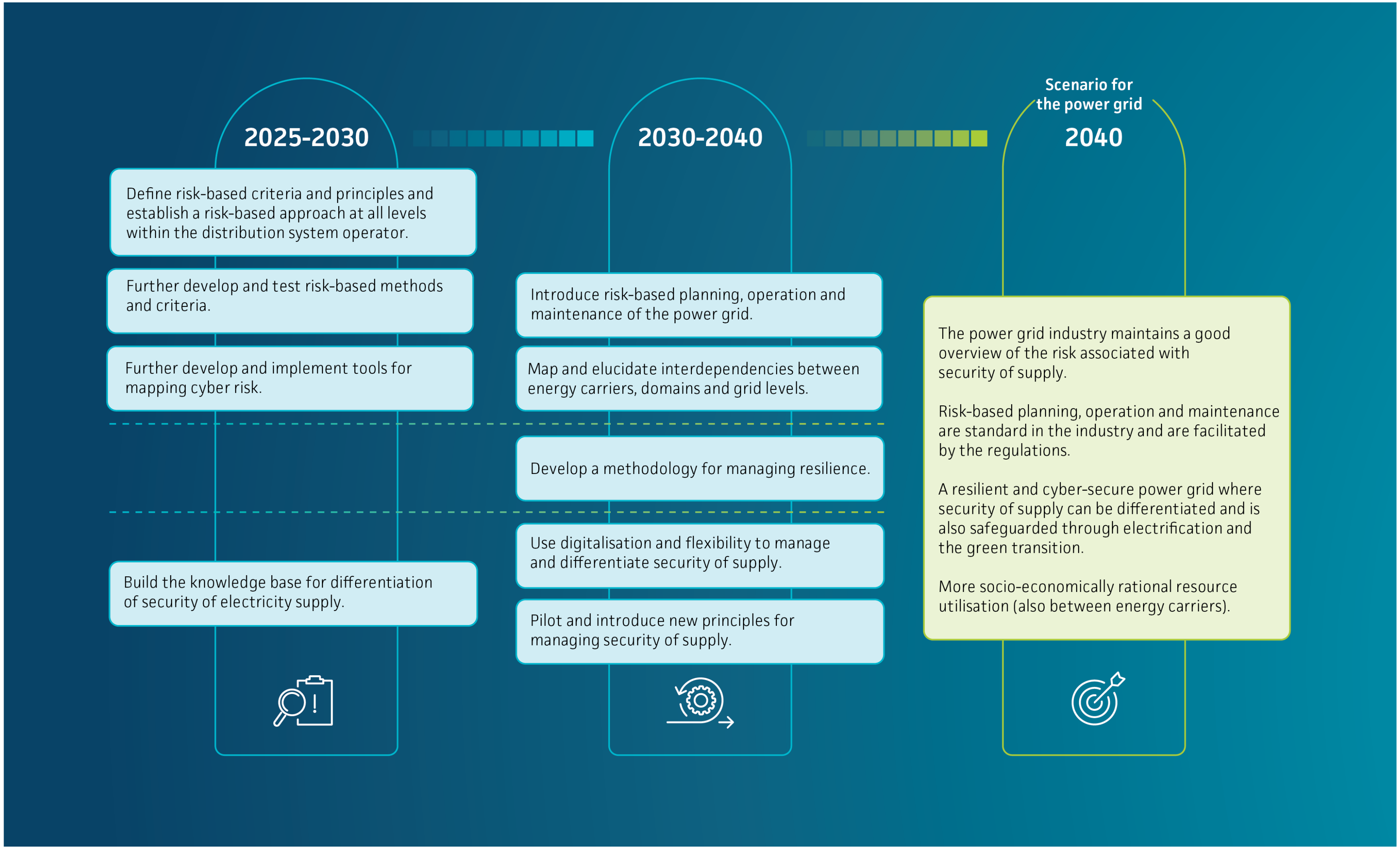


Table 2 Roadmap for Principal Conclusion 2: Flexibility in the consumption, generation and storage of energy must be made use of to achieve better utilisation of the power grid.

2025-2030	2030-2040	Scenario for the power grid 2040
Further develop methods for mapping available grid capacity, both in the short and the long term. Further develop tools that show available flexibility. Pilot the use of flexibility for active grid operation. Establish a system for co-ordinated use of flexibility across grid levels.	Develop and introduce standardised flexibility products. Implement methodology in tools to optimise flexibility use across grid levels.	The distribution system operators use tools in the operations centre that detect where there is a need for flexibility (throughout the grid level) and where the providers are, and automatically interact with the provider/aggregator.
Develop models for the value of flexibility and verification of delivered flexibility. Develop business models for flexibility. Further develop marketplaces for trading between distribution system operator, aggregator and customer.	Implement the flexibility models in tools for grid operations. Implement tools that automatically interact with flexible resources.	The entire flexibility value chain has been established and the grid is better utilised with the help of flexible resources, co-ordinated and optimised across grid levels. Distribution system operators are experienced buyers of flexibility, utilising a combination of market-based and contract-based flexible resources on a large scale.
Investigate the societal and social consequences of (continuously) utilising flexibility in the power system. Introduce regulations that facilitate power co-ordination, production sharing and activation of flexibility.	Investigate the societal and social consequences of (continuously) utilising flexibility in the power system. Implement a new standard connection agreement that makes customers' flexibility available.	All products that use (a lot of) electricity are supplied with facilities for control by a third party. The customer of the future is a flexible resource, i. e., an active customer who has the ability and willingness to contribute flexibility and has a connection agreement that enables load management without needing to have a conscious relationship with this.

Table 3 Roadmap for Principal Conclusion 3: Security of electricity supply is compromised by extreme weather, cyber threats, increased operating loads and increased complexity of the power system, and must be handled differently in the future



5 Conclusion

This report has described the strategy and roadmap for the transition to a flexible and intelligent power grid up to 2040. This is based on results from CINELDI, a centre for environment- friendly energy research (FME). The strategy is based on eight years of research and piloting at CINELDI and consists of several recommendations to enable the transition to the intelligent, flexible, robust and cost-effective power grid of the future. To meet the challenges posed by the green transition, the power grid must facilitate growth in consumption and production, the electrification of new types of consumption, and better utilisation of resources. This report highlights three principal conclusions that are crucial to achieving this:

1. **Widespread digitalisation and automation are necessary to gain insight into and enable control of the power grid.** To enable the optimal utilisation of the grid we must have an insight into how it operates and be able to control it using active measures. This necessitates digitalisation and automation.

2. **Flexibility in the consumption, generation and storage of energy must be made use of to achieve better utilisation of the power grid:** Flexibility must be implemented to be able to connect as much consumption and new generation as possible, and to achieve better utilisation of the grid.

3. **Security of electricity supply is compromised by extreme weather, cyber threats, increased operating loads and increased complexity of the power system, and must be handled differently in the future.** Digitalisation and flexibility provide opportunities for discovering new ways of managing security of supply.

Each principal conclusion describes measures that form the basis of a roadmap for the period 2025-2040 and must be implemented in collaboration between distribution system operators, technology suppliers, industry associations, authorities and research and education institutions.

The measures in the roadmap must be seen in context to ensure that technological advances, industry practices and regulatory frameworks go hand in hand to meet the necessary requirements and realise the targets set for 2040. This requires co-operation and interaction between the various stakeholders for continuous development, testing and piloting of solutions.

The results and recommendations from this strategy process provide a basis for navigating the complex issues related to the adaptation of the power system for the green transition, where close co-operation between the various stakeholders is key to the power grid of the future. Without such co-operation, the transition will undoubtedly fail.

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Centre for intelligent electricity distribution
- to empower the future Smart Grid