WHITE PAPER 0

Origins and Operational Record

Twenty-five years of quantified grid risk, 2001–2026: the projects, publications and installations behind the White Paper series

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WP1–WP3 ARGUE WHAT RISK-BASED OPERATION CAN DO.

WP0 DOCUMENTS THAT IT HAS ALREADY BEEN DONE.

This paper forms the foundation of a series. White Paper 1 presents the three-layer framework for risk-based grid operation, White Paper 2 extends it to Virtual N-1, and White Paper 3 applies it to data centres as flexible load. White Paper 0 documents the record they build on.

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Glossary of Acronyms

Acronym	Definition
BKK	BKK Nett, regional grid company in western Norway
DSA	Dynamic Security Assessment
EENS / ILE	Expected Energy Not Supplied (Norwegian: ikke levert energi)
EVM	Energiverk Mongstad (gas-fired power plant at Mongstad)
GARPUR	Generally Accepted Reliability Principle with Uncertainty modelling and through probabilistic Risk assessment (EU FP7 project)
KILE	Kvalitetsjusterte inntektsrammer ved ikke levert energi (Norwegian regulatory cost of energy not supplied)
MTTF / MTTR	Mean Time To Failure / Mean Time To Repair
N-1	Single-contingency operational criterion
NVE	Norwegian Water Resources and Energy Directorate (regulator)
PRA	Probabilistic Risk Assessment
PROMAPS	Reliability analysis program built on the Markov–Kronecker method; later Promaps Online and Promaps Realtime
RFF	Regionale forskningsfond (Norwegian regional research funds)
SCADA	Supervisory Control and Data Acquisition
SMS	System minutes: expected unavailability expressed as minutes per year, used as system risk indicator
TSO / DSO	Transmission / Distribution System Operator

Table 1

Source Attribution

Throughout this paper, a distinction is made between:

- **“Published”**: results reported in peer-reviewed papers, conference proceedings or textbooks (listed in References).
- **“Project report”**: results documented in client reports from the projects described. Several of these are confidential; they are summarised at the level of question, method and general finding, without client data.
- **“Operational experience”**: observations from live use of the online and real-time tools at system operators.
- “Contemporary company record”: dated company news, contract announcements and product records that document what was stated, contracted or planned at the time. These are useful contemporary evidence, but are not treated as independent verification.

Numbers quoted from project reports apply to the system, year and assumptions of that study. They illustrate what the method could show, not general values. Results from confidential client reports are given as general findings, without client-specific data.

Executive Summary

The risk-based framework of WP1–WP3 was not designed on paper. It grew out of 25 years of projects, each answering a concrete question for a grid owner, and each leaving behind a lesson that shaped the next step.

The journey has four stages:

- **A method (2001–2004).** A regional grid company needed to know what faulty protection equipment cost under the new KILE regulation. The answer required Markov models too large to build directly. Composing them from small unit models with Kronecker operators reduced a model of about 6 million states to 17 small ones (PMAPS 2004).
- **Proof in real grids (2005–2013).** More than twenty projects for Statnett, Landsnet, National Grid UK, StatoilHydro, Eni and Gassco tested the method on meshed transmission grids, offshore electrification, substation design and process plants. They showed that reliability could be computed for whole systems, priced in KILE terms, and compared across alternatives. Goliat (2008–2010) and the Troll A compressors (2010–2011) produced the first connections of large new load on the condition that it could be curtailed or disconnected, and the method was transferred to overpressure risk in gas processing for Gassco and Equinor.
- **Real-time operation (2009–2015).** Statnett and Goodtech built an online regularity calculator. It was put into online operation at Statnett in October 2013 as an operational prototype on a model of more than 3,500 nodes and 9,000 branches, calculating over 20,000 fault combinations in under 500 seconds, while testing and further development continued. Weather-dependent failure rates were added with StormGeo.
- **Daily use (2015–today).** Promaps Realtime ran at Elvia, Landsnet, Tensio, Lede and Dalane Nett. At Dalane, the same model supported operation, maintenance prioritisation and reinvestment decisions. During the Møre blackout of 6 December 2014, Promaps Online had shown an elevated risk state for more than 19 hours before the fault. A later study-mode replay indicated that the loss of supply would most likely have been avoided had the earlier local production been maintained.

Three lessons run through the whole record. First, deterministic N-1 hides both excess margin and real risk; quantified risk shows both. Second, risk only becomes useful when operators can see it at a glance. Third, controlled disconnection of selected load is an old and proven tool, and quantified risk tells you when and where to use it.

These lessons are the foundation of WP1 (the three-layer framework), WP2 (Virtual N-1) and WP3 (data centres as grid resources).

1. Introduction

WP1–WP3 argue what risk-based operation can do for grid capacity. This paper shows where that argument comes from: the projects, publications and installations behind it, and what each one taught.

WP0 has three purposes:

1. Give the series one citable record of origins, so the later papers can refer to it instead of repeating background.
2. Make the development path visible, so readers can see why the framework looks the way it does.
3. Separate research, pilot and operation clearly, with dates and parties.

Each project is described in the same four steps: **Question** (what the client or the project team wanted to find out), **Approach** (what was modelled), **Result** (what the analysis showed) and **Lesson** (what was carried forward). Publications are summarised the same way in Section 8.

The paper follows the timeline. Section 2 covers the origin of the method. Sections 3–5 cover the project years, grouped by type of problem. Section 6 covers the move to real time, and Section 7 daily operation. Sections 8–9 cover publications and recognition. Section 10 describes where the work stands today and links the lessons to WP1–WP3.

2. The Starting Point, 2001–2004

The method began with a regulatory cost, not a research agenda. When NVE introduced KILE on 1 January 2001, grid owners started paying for energy not supplied, and the reliability of their equipment became an economic question.

2.1 The user need (2001)

Question. Faults in protection and control equipment caused KILE costs of about NOK 60 million per year in Norway (Aabø and Kjølle, 2001). Yngve Aabø, section manager for grid engineering at BKK Nett, wanted a method to evaluate the reliability of such equipment and compare alternatives when a substation is renewed.

2.2 The master thesis (2002)

Approach. Arne Brufladt Svendsen's NTNU master thesis, carried out at BKK Nett and Aker Elektro, built a reliability model for transformer stations. It combined fault-tree analysis for the protection systems with composite Markov models for protection, network and local control equipment. The model was applied to Lille Sotra transformer station, comparing four protection configurations for new numerical equipment.

Result. The differences in station availability between the four configurations were small. The thesis recommended single protection with two-out-of-three measuring units, and reduced maintenance on numerical equipment.

Lesson. The engineering answer was modest, but the modelling problem was not. Combining primary equipment, secondary equipment and network states produced Markov models far too large to build by conventional means.

2.3 The Markov–Kronecker solution (2002)

The thesis supervisor Tørris Digernes (then Aker Elektro, later MathConsult) solved the size problem that was published in Arne Brufladt Svendsen’s NTNU master thesis. Each component is described by a small unit model, and the system model is composed from them using Kronecker matrix operators instead of being enumerated state by state. In the first published example, a complete conventional Markov model of about 6 million states was replaced by 17 small unit models (PMAPS 2004).

Lesson. The practical size limit for Markov models moved from about 100 states to almost unlimited. Reliability analysis of complete meshed grids, with protection and control included, became feasible.

2.4 Textbook recognition (2004)

The method was included in Rausand and Høyland, *System Reliability Theory*, 2nd edition (2004), section 8.8 on complex systems. The same year, PMAPS 2004 extended it with power flow and economic models, so that reliability could be expressed as expected cost.

Lesson. From the start, the method linked probability, consequence and cost. That link is the core of every later step, including the risk metrics used in WP1.

3. First Applications: Regional Grids and Iceland, 2005–2009

The first projects asked one question: does the method work on a real, meshed transmission grid? Statnett and Landsnet answered it in parallel, and Landsnet's projects turned the calculation into a tool operators could use. Development in this period was supported by the Research Council of Norway (Doble presentation, 2007).

3.1 Sognenettet, Statnett (2005–2006)

Question. Can the method be used to analyse Statnett's grids at all? Statnett was interested in its analytical ability and development potential rather than in a fully detailed study (Project report, 2006).

Approach. The ring-operated Sogn grid was chosen as test object. It has large power exchange at several nodes and industrial load at Høyanger that does not follow normal seasonal variation. Two model classes were used: a power flow model that maximises net economic benefit including losses, and a reliability model built from unit models.

Result. The method handled ring operation and complex meshed structures, input data were easy to set up, and calculations ran fast. Planned funding from Innovasjon Norge was not available, so Statnett financed a reduced scope.

Lesson. The report already noted that the short calculation time made the method especially suited as decision support in control centres. The idea of online use dates from here, seven years before it was realised.

3.2 Landsnet risk and reliability studies, Iceland (2005–2007)

Question. How reliable is power delivery in Landsnet's 132 kV and 220 kV systems, and what drives it? The work was part of an industrial and regional development (IRD) project granted in January 2006, with Norwegian state co-funding.

Approach. The studies covered the eastern system (including Kárahnjúkar), the western 220 kV system around Reykjavík (final IRD phase) and the northern 132 kV system (2007). Program efficiency was improved between phases. Line failure rates were split into good-weather and bad-weather states, using Icelandic fault statistics.

Result. The level of spinning reserve had a clear influence on delivery reliability at the large load points, including the ISAL aluminium smelter and Brennimelur.

Example. At a 450 MW load point (Brennimelur) at full demand, raising spinning reserve from 70 MW to 130 MW reduced the failure probability from $1.29 \cdot 10^{-4}$ to $3.24 \cdot 10^{-5}$, about four times lower, and the outage frequency from 0.75 to 0.27 per year (Figure 1).

Eksempel: **Power delivery probability**

70 MW spinning reserve:

Internal branch no.(#) : 28
Branch no. : 28
Branch description : Consumption 1: 450 MW

Demand situation no. [%]	Probability		Mean duration		Departure frequency
	Functioning	Failure	Functioning [year]	Failure [h]	[1/year]
80	0.999988	1.19066e-005	12.1871	1.27115	0.0820529
90	0.999953	4.70647e-005	2.73734	1.12862	0.365301
100	0.999871	0.000128501	1.34181	1.51062	0.745167

130 MW spinning reserve:

Internal branch no.(#) : 28
Branch no. : 28
Branch description : Consumption 1: 450 MW

Demand situation no. [%]	Probability		Mean duration		Departure frequency
	Functioning	Failure	Functioning [year]	Failure [h]	[1/year]
8	0.999988	1.19008e-005	12.1977	1.27164	0.0819816
9	0.999988	1.19465e-005	12.153	1.27185	0.0822831
10	0.999968	3.23501e-005	3.71918	1.054	0.268868

Figure 1. *State-dependent delivery reliability at a 450 MW load point (Brennimelur, Landsnet model) with 70 MW and 130 MW spinning reserve. Demand situations 8, 9 and 10 in the lower table correspond to 80%, 90% and 100% demand in the upper table. At 100% demand, failure probability falls from $1.29 \cdot 10^{-4}$ to $3.24 \cdot 10^{-5}$ and outage frequency from 0.75 to 0.27 per year. Source: What is PROMAPS, presentation at Doble, 2007, based on the Landsnet study.*

Lesson. Reliability depends on the operating state, not only on the network. Spinning reserve, load level and weather all move the risk, so a static study can only give a snapshot.

3.3 Integrated reliability model, Landsnet (2007–2008)

Question. Can the three regional models become one tool that Landsnet's own staff can use?

Approach. The three PROMAPS models were merged into one model of the full 132 kV and 220 kV system. An active single-line diagram replaced script-based simulation. All input data moved to Excel to prepare connection to SCADA and other tools.

Result. The tool showed a low, medium or high risk indicator per area, and calculated system minutes (SMS) and expected reliability cost on screen. Cases with and without Kárahnjúkar, high and low spinning reserve, and summer and winter load were compared with Landsnet's historical SMS average for 1998–2007.

Lesson. This was the first time the risk indicators later used in operation (SMS, expected cost, colour-coded risk level) appeared together in one operator-style interface. Structuring input data for SCADA was the first concrete step toward real time.

4. Offshore Electrification and Process Industry, 2006–2019

Electrifying offshore installations from shore placed large new point loads on onshore grids that were not built for them. These projects showed, more clearly than any other, that a grid can pass a deterministic load flow check and still lose regularity. They also produced the first conditional connection of a large load based on automatic disconnection.

4.1 Early offshore studies: Gjøa and Goliat (2006–2010)

Gjøa. A regularity analysis was carried out for supply to the Gjøa platform from Lutelandet (SFE, 2006), applying the method to the full chain from the onshore grid to the offshore installation.

Goliat FPSO, Hammerfest (Eni, 2008–2010).

Question. Could up to 60 MW of new load for electrification of the Goliat FPSO be connected to the existing power system in Finnmark without an unacceptable deterioration in regional security of supply?

Approach. Eni commissioned power-system and regularity analyses of the existing grid and the impact of the additional Goliat load. Public government documentation confirms that the power-system analyses were subsequently reviewed and verified by Statnett in dialogue with NVE. The regulatory record also considered changes in N-1 and N-0 operation, periods of reduced security of supply, special regulation and possible load disconnection at Goliat.

Result. The work concluded that supply of up to 60 MW could be accommodated without special measures in the regional transmission network. The connection could increase the duration of constrained operating states in the wider system, but operational measures - including reduced land-power import and, if necessary, load disconnection at Goliat - could limit the consequences. Statnett recommended that Goliat could be supplied with up to 60 MW from shore. The analyses formed part of the documented basis for the subsequent licensing process.

Lesson. A large new industrial load did not have to be treated simply as either "connectable" or "not connectable". By analysing the actual system consequences, their likelihood and the available corrective actions, additional load could be accepted while explicitly managing the resulting risk. Goliat is therefore an early precursor of the conditional-connection principle later developed more explicitly in the Troll A compressor project and in WP2 and WP3.

> **Source note.** Public confirmation is available in St.prp. nr. 64 (2008–2009), sections 2.3 and 4.38. It records that Eni's power-system analyses were reviewed and verified by Statnett in dialogue with NVE, and that Statnett recommended supply of up to 60 MW while the regulatory discussion also addressed N-0 operation, special regulation and possible load disconnection.

4.2 New power supply to Troll A (StatoilHydro, 2007–2008)

Question. What happens to the onshore grid and process plants when power to the Troll A platform is increased, and which onshore connection point is best: Kollsnes, Mongstad, Stord or Lutelandet? (Project report, 2008.)

Approach. Load flow and regularity analyses for several time periods and load levels at Troll A, covering the BKK area, the new gas-fired plant at Mongstad (EVM) and a possible 300 kV link Kollsnes–Mongstad.

Result. Load flow and voltage showed no problems in the grid as it was. The regularity analysis showed problems already: in heavy load, the BKK area was at or beyond Statnett's proposed requirement of less than 15 system minutes. EVM would improve the situation, but its full effect required the Kollsnes–Mongstad link and splitting the load between Kollsnes and Mongstad. Regularity costs rose sharply with load. Stord was considerably more expensive, and Lutelandet carried schedule risk.

Lesson. The deterministic electrical check and the probabilistic regularity check gave different answers for the same grid. This is the clearest early example of the WP2 argument: N-1 compliance says nothing about the probability or consequence of what lies beyond it.

4.3 Regularity challenges of offshore electrification (ESREL 2009)

The Troll A experience, together with a documented decline in regularity in central Norway after a large offshore installation was connected, was generalised in ESREL 2009. The paper argued that grid extensions for offshore loads are usually evaluated only from an electrical point of view, not for total system regularity.

4.4 Single-sided supply of Kollsnes (StatoilHydro, 2008–2009)

Question. BKK planned to supply Kollsnes from one side via 300 kV. What would that mean for regularity, and how should the load-shedding system at Kollsnes be designed? (Project proposal, 2009.)

Lesson. Load shedding of large industrial load was already an accepted design element. The open question was how to size and trigger it, which requires quantified risk.

4.5 Compressors 3 and 4 for Troll A (Statoil, 2010–2011)

Question. Can two new electric pre-compressors for Troll A, up to 50 MW each, be supplied from shore at Mongstad or Kollsnes before the planned grid reinforcements are in place? Load was expected to rise from about 45 MW in 2015 to over 100 MW by 2018 (Teknisk Ukeblad, 2010).

Approach. Network and regularity analyses for several operating situations specified by Statoil, using conservative loads and no grid upgrades, formed part of the technical basis for Statoil's licence application of June 2010. A follow-up in 2011 studied the case where the Kollsnes–Mongstad 300 kV link was not yet in service. Cost of energy not supplied was used as the common indicator (Project report, 2010).

Result. The analyses found that the compressors could be connected at Mongstad on condition that automatic load-shedding was implemented for the new pre-compressors. Connection at Kollsnes without the Mongstad link would strain the BKK grid, increase load disconnection at Kollsnes and Troll A in fault situations, and sharply reduce regularity. This finding was reported publicly at the time: Statoil’s own analysis indicated that supply from Kollsnes would reduce grid reliability unless the Mongstad–Kollsnes connection was built (Teknisk Ukeblad, 2010).

Public record. The connection was debated openly. Statnett and BKK Nett asked that it not be allowed before the Sima–Samnanger and Mongstad–Kollsnes reinforcements, pointing to an already strained supply into the Bergen area. NVE recommended a licence for the Kollsnes alternative in January 2011, conditional on timely reinforcements, and noted that temporary system protection

would add societal cost (NVE, 2011). In September 2011 the Ministry of Petroleum and Energy granted the licence and accepted somewhat weaker security of supply for a limited period: Troll A could connect as a temporary solution using system protection and disconnection until the reinforcements were completed (Teknisk Ukeblad, 2011).

Lesson. This is a direct, publicly documented precursor of Virtual N-1 (WP2). A large new load was allowed onto a grid that could not yet carry it firmly, on condition that it could be disconnected when the system required it. The trade-off between security of supply and the value of the new load was made explicitly, at ministry level, but case by case and without a common risk metric. WP2 proposes to make that trade-off systematic and quantified.

> **Source note.** Public confirmation is available in NVE's background for its recommendation (31 January 2011, ref. 201003047-29) and in Teknisk Ukeblad's reporting of September 2010 and of the ministry decision of 13 September 2011.

4.6 Process industry: Gassco and Equinor (2011–2019)

Question. Can the same unit-model methodology used for power-system reliability be adapted to quantify overpressure risk in a complex gas-processing flare system, and provide engineering answers faster?

Approach. Gassco asked Goodtech whether the PROMAPS methodology could be adapted to the flare-system problem. A pre-project transferred the combination of reliability models and flow models to the process-safety application. The work continued through several Gassco phases (2011–2014) into OPRA, the overpressure risk analyser.

Result. A contemporary Goodtech account states that the pre-project concluded that PROMAPS could be adapted to the problem and that a software package was planned for installation at Gassco in 2013. In November 2018, Equinor contracted a pilot installation of Promaps OPRA for part of the Kårstø flare system, including six licences, model completion and one year of maintenance and support, with an option to extend the model to the complete flare system. A second Kårstø phase followed in 2019.

Lesson. The Markov/unit-model architecture was not tied to electrical grids. It could be transferred to another large interconnected transport and safety system in which probability, flow and consequence interact.

5. Risk-Based Design and Asset Management, 2008–2013

The design projects showed that the right substation layout depends on where the substation sits in the system, and that intuition about which design is "simpler" or "safer" is often wrong once secondary systems are modelled.

5.1 Station design reliability, National Grid UK (2008)

Question. How do two National Grid substation configurations, a double busbar and a 4-switch meshed busbar, compare in delivery reliability and number of disturbances? And what changes when a fifth transformer is added? (Project report, 2008.)

Approach. Both configurations were modelled with protection and control included, connected either to a meshed system or to four separate radial systems below the substation, and analysed for N-0 to N-3 situations.

Result. With a meshed system below, both configurations had very high availability at full load. With four radial systems below, the double busbar was considerably stronger, with a mean time to failure roughly three times longer. Contrary to expectation, the meshed design with fewer components had about half again as many disturbances, because of its more complex secondary system and exposure to ferroresonance.

Lesson. The value of a design depends on the network around it, and secondary equipment can dominate the result. Both points need a system model; neither shows up in component-by-component reasoning.

5.2 Optimal substation design, Njarðvíkurheiði, Landsnet (2009)

Question. Is a single breaker, single busbar substation a feasible alternative to double breaker, double busbar at a planned connection point for generation and industrial load in western Iceland? (Project report, 2009.)

Approach. A pre-project upgraded Landsnet's PROMAPS model and assessed the substation's importance in the system. The two designs were then compared for delivery reliability and cost for connected loads and power exchange.

Result. The substation had high redundancy from the surrounding system. The simpler design was found feasible, provided commissioning quality was high and protection and control had self-monitoring. An extra breaker splitting the busbar was recommended if common-mode failure data remained uncertain.

Lesson. Where the system provides redundancy, the substation need not duplicate it. Quantified system risk can justify a cheaper design without reducing security, which is the investment counterpart of the operational argument in WP1.

5.3 Asset management and maintenance (2012–2013)

The method was also used for risk management of Statnett's value chain under PAS 55 (2012) and for reliability analysis of Steinsland transformer station for BKK Nett (2013).

6. Toward Real-Time Risk, 2007–2016

Between 2007 and 2013 the method moved from offline studies to a tool running on the live national grid model. Each step answered a practical question about what operators need: a usable picture, a policy beyond N-1, speed at national scale, and weather.

6.1 Risk management in operation: first operator prototype, Statnett (2007)

Question. Can reliability calculations give control-room operators better information about current risk, and about how risk changes with changes in grid and production? (Project report, 2007.)

Approach. A model of the western Norway grid was built in PROMAPS, with an active operator display (PROMAPS_SCADA) based on the single-line diagram. Three historical operating hours were analysed, with thermal limits at 100% and 120%.

Result. Risk was shown with dynamic colour coding: yellow for danger zone, red for unacceptable level. In the heavy-load case, two load points in the Bergen area were indicated red. KILE cost and thermal loss cost were reported side by side as total system cost.

Lesson. Operators need risk "at one look at the screen". Putting interruption cost and losses on the same cost scale also made the trade-off between security and utilisation explicit, which is the logic of the WP1 Decision Layer.

Contemporary evidence of the online ambition. A 2007 presentation of PROMAPS at Doble described it not only as an offline reliability tool, but as a system intended to support engineers in maintenance, investment strategy, system design and operation. It also stated that work was under way to connect PROMAPS to the control centre of a large Norwegian power company for online monitoring and evaluation of power-delivery reliability. Because the company was not identified in the presentation, this contemporary statement is kept separate from the later, explicitly documented Statnett online programme. The same presentation used the Landsnet model to illustrate state-dependent reliability (Figure 1, Section 3.2).

6.2 Risk management of operation, Statnett R&D (2009–2013)

Question. Can reliability be calculated online, with minimal delay between process values and risk indices, on the main Norwegian grid?

Approach. Statnett (Jan Ove Gjerde, R&D, and Stig Løvlund, regional operation centre North) defined the scope in 2009, and Goodtech and Statnett signed a development agreement the same year. Four R&D phases followed.

Result. An online regularity calculator was developed (PMAPS 2012). The papers drew the operational conclusion directly: with such a tool, an operator can move beyond the conservative N-1 criterion and operate to a maximum accepted risk level, or to minimum total cost.

Lesson. This is the first published statement of the position later developed in WP2. It was made from operational development work, not from theory.

6.3 Online operation at national scale (2013–2015)

Result. The calculator was put into online operation at Statnett in October 2013 as an operational prototype/test installation connected to the live national-grid environment. Contemporary records describe both sides of that status: it was in operation and connected to Statnett's SCADA environment, while testing, fault correction and further development continued. The Norway model covered all of Statnett's 132, 300 and 420 kV grid and the underlying 1–132 kV system from the EMS, with more than 3,500 nodes and 9,000 branches. More than 20,000 fault combinations were calculated in under 500 seconds on a multi-core processor, giving reliability for all primary and secondary components and delivery reliability for all loads.

Representation. With risk changing every 10 minutes across a 7,000-branch system, a single-line diagram was no longer enough. ESREL 2014 tested layouts in which the grid is redrawn by risk level

and power flow instead of geography. Graph layout with clustering worked best: it showed the most critical cuts and the risk level per area at a glance, with detail on zoom.

Lesson. At national scale the bottleneck moved from calculation to perception. This is the origin of the representation argument in WP1 Section 3.8.

6.4 Weather-dependent risk (2013–2016)

Question. How much does weather change component failure probability, and how should that enter online calculations?

Approach. Research projects with StormGeo, funded through regional research funds (RFF), derived weather-dependent correction factors from fault statistics and weather data. About 25% of line failures in Norwegian statistics are caused by wind; that share of each line's failure rate was scaled by a wind factor.

Result. The projects confirmed a strong correlation between line faults and wind strength (ESREL 2015). During storm Tor in 2016, Promaps was run on the national model with weather correction. A later account from the Regional Research Fund reported that the pre-event forecasts of where outage risk was highest corresponded strikingly well with the areas where more than 30,000 households actually lost supply. A study on the Icelandic grid, using 10 years of weather data and a two-year blind test, found that weather dependence makes risk positively skewed: long low-risk periods and short high-risk peaks (Journal of Risk and Reliability, 2017).

Lesson. Average failure rates understate risk when it matters and overstate it the rest of the time. A static margin sized for the average is therefore both too large and too small, which is the core of the WP1 and WP2 critique of deterministic N-1.

7. From Prototype to Daily Operation, 2014–Today

From 2015 the tool moved from a TSO prototype into commercial operation at regional system operators in Norway and Iceland. The Møre blackout in December 2014 provides a rare operational record: the developing risk state was captured in Promaps Online before the fault, and the stored operating state was subsequently replayed and analysed in study mode.

7.1 The Møre blackout, 6 December 2014

Question. Could the outage on the 420 kV line Ørskog–Viklandet have been foreseen, and could the loss of supply have been avoided?

Operational record. The event was observed in Promaps Online. At 19:32 on Saturday 6 December 2014, immediately before the line fault at about 19:35, the online model identified the loads that would not be supplied if Ørskog–Viklandet tripped. The actual outage affected between 80,000 and 90,000 customers in about 25 municipalities, corresponding to at least 150,000 people; supply was restored at about 21:45.

Post-event analysis. The stored risk history showed that at 00:12 on 6 December Ørskog–Viklandet moved from outside the national top-100 risk ranking to third highest. The Promaps/KeyBrowser risk curve showed an elevated risk state for more than 19 hours, associated with down-regulation of production in the Møre area (Tafjord). A subsequent study-mode replay tested the operating state from Friday evening before that down-regulation. With Ørskog–Viklandet removed in that state, the model showed that all loads would still have been supplied.

Lesson. The operational record shows that the system vulnerability was visible in the quantified risk picture many hours before the actual fault. The study-mode counterfactual indicates that maintaining the earlier local-production state would have avoided loss of supply for the modelled line outage. The original presentation explicitly notes that other, unmodelled factors may also have contributed. This is the operational evidence behind the early-warning use case in WP1.

> **Source note.** Promaps Online risk history and study-mode analysis of the Ørskog–Viklandet event (operational event presentation). Figure 2 is a schematic redrawing; the original control-room screenshots are not reproduced.

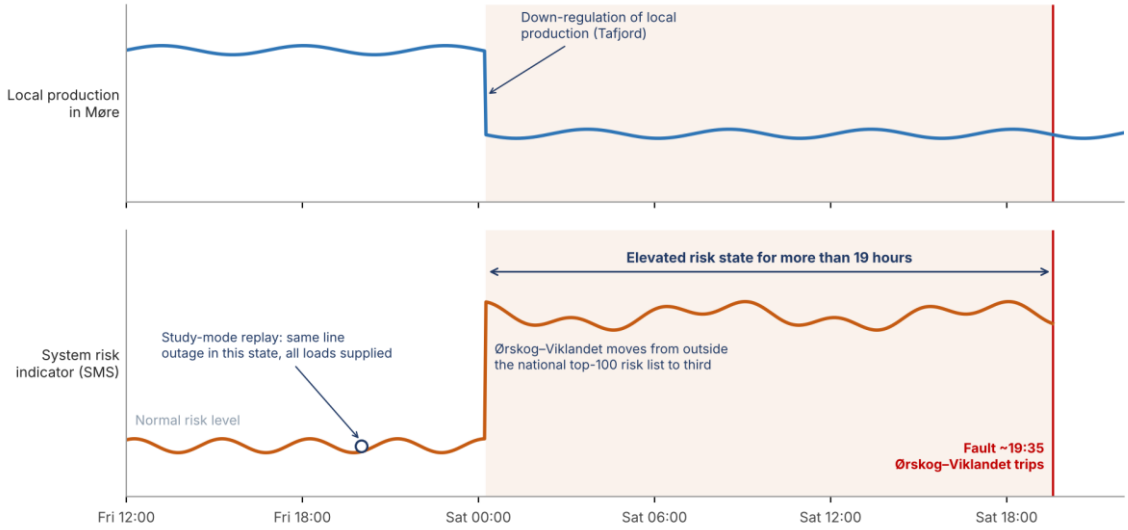


Figure 2. *The Møre event, 5–6 December 2014 (schematic). Local production in Møre was down-regulated shortly after midnight, and the Promaps Online system risk indicator (SMS) then stayed elevated for more than 19 hours until Ørskog–Viklandet tripped at about 19:35. A study-mode replay of the same line outage in the Friday-evening operating state left all loads supplied. Schematic redrawing based on the operational risk history; curves are illustrative, not measured values.*

7.2 Commercial operation

Installations known so far add up to roughly 28 operating years. The count includes only systems that were actually installed and operated; signed agreements or planned test installations that did not enter operation are excluded.

Operator	Country	Product	Period	Operating years (approx.)
Tensio (former NTE Nett area)	Norway	Promaps Realtime	2018–2025	7
Lede (Skagerak Nett)	Norway	Promaps Realtime	2018–2022	4
Dalane Nett	Norway	Promaps Realtime	2018–2021	3
Landsnet	Iceland	Promaps Realtime	2016–2021	5
Elvia (Hafslund)	Norway	Promaps Realtime	2015–2022	7
Statnett	Norway	Promaps Online operational prototype	2013–2015	2

Table 2

In operation, the tool gave four near-real-time indicators: expected energy not supplied (MWh/h), expected KILE cost (NOK), system minutes (minutes per year) and availability (%). Additional applications trended results over time, supported study-mode analysis and replayed historical risk curves.

Deployment record. Contemporary company records document separate 2018 leasing agreements with several regional grid operators, including NTE, Skagerak Nett and Dalane Energi Nett. NTE entered installation and trial preparation from March 2018; Skagerak and Dalane followed later that year. The operational history records continued use at the former NTE network (now part of Tensio), Lede/Skagerak and Dalane.

Use cases and boundary of the record. Dalane's 2018 agreement explicitly covered operational use, maintenance prioritisation and reinvestment prioritisation, showing one model being used across several decision horizons. Two further agreements from 2018, one leasing agreement and one intention agreement for a test installation, did not lead to documented operation and are not counted. After a grid merger, Promaps Realtime continued only on the former NTE part of the Tensio network, not across the full merged grid.

Lesson. The move from one TSO prototype to several regional and distribution operators showed that the method could run as a product on different grids and voltage levels. Dalane also demonstrated that the same probabilistic model could support operation, maintenance and reinvestment decisions rather than being confined to one organisational process.

7.3 Analysis services built on the operational model (2014–2020)

Hindcast for NVE. The operational model and stored data allow an event to be replayed: what happened, why the consequences became what they were, and whether they could have been avoided. Møre 2014 was the example presented to NVE.

Investment analyses. Experience from Troll A, the compressor projects, Goliat and an alternative supply route to Nyhamna for Statnett was condensed into a method: analyse a large enough area, use a representative base case, do not over-simplify reliability, run enough scenarios, and compare alternatives by net present value including KILE.

Regularity analyses. The Haugaland power system for Haugaland Kraft (2020) applied the same approach to a regional grid.

Digital model integration, Lyse Elnett (2020). In an R&D project, Promaps Technology was commissioned to develop a data interface between Promaps Realtime and Lyse Elnett's UNC model environment, based on Esri ArcGIS Utility Network. The stated objective was near-real-time and forecast risk analysis, while also identifying needs across Lyse Elnett's work processes and adapting Promaps Realtime toward a uniform, holistic risk analysis of the power system across the value chain.

Lesson. One model can serve operation, post-event analysis, maintenance, investment planning and multiple organisational work processes. The Dalane and Lyse records make that shared baseline explicit; it is what WP1 calls the common operational reference frame.

8. The Publication Record, 2003–2018

Eleven papers document the method as it developed, from the first cost-based reliability model in 2003 to weather-dependent online risk in 2017. Read in sequence, they trace the same path as the projects: method, scale, online operation, representation and weather.

Year	Paper and venue	Question	Result
2018	Digitalization of the power business: How to make this work? ESREL, Trondheim	How can digital tools such as online risk assessment be taken into routine use?	Full text not reviewed for this paper.

Year	Paper and venue	Question	Result
2017	Modelling Weather Dependence in Online Reliability Assessment of Power Systems. Journal of Risk and Reliability	Does a weather-dependent failure rate model predict outages better than a constant one, and how does it change risk estimates?	Tested on 10 years of Icelandic data with a two-year blind test. Weather dependence matters for risk and maintenance assessment, and makes risk positively skewed: rare high-risk periods.
2015	Online Reliability Calculations of Power Systems with Forecasted and Real Time Weather Influence. ESREL, Zurich	How should forecast and real-time weather enter online reliability calculations?	Strong correlation between line faults and wind confirmed; correction factors derived and implemented. Reports Statnett online operation from October 2013.
2014	Abstract representation of power system networks as a function of regularity properties. ESREL, Wrocław	How can operators see risk changes every 10 minutes across a 7,000-branch grid?	Graph layout with clustering, driven by risk and flow, lets operators identify critical cuts and area risk at a glance.
2012	Online reliability assessment of power system. PMAPS, Istanbul	Can delivery reliability be calculated online for a TSO, and what does that enable?	Online regularity calculator developed with Statnett. Operation can move beyond conservative N-1 to a maximum-risk or minimum-total-cost policy.
2009	Reliability analysis including load flow and power demand in power system. AR2TS, Loughborough	How do load flow and demand level change delivery reliability?	Full text not reviewed for this paper.
2009	Power system regularity challenges connected to electrification of large-scale offshore installations from land. ESREL, Prague	What happens to onshore regularity when large offshore loads are connected?	Such extensions are usually judged only electrically; a documented case in central Norway showed falling regularity. Total system regularity must be assessed.
2007	Maintenance planning based on simulation of power delivery reliability and economic consequences. Doble, Germany	Can simulated delivery reliability and economic consequences support maintenance and broader engineering decisions?	*Paper text not located; summary from the accompanying presentation.* PROMAPS combined probabilistic reliability with an optimisation-based load-flow model and evaluated delivery reliability and economic consequences as functions of load, generation, spinning reserve and network configuration. The presentation positioned the model for maintenance, investment, system design and operation, and pointed toward online control-centre use.

Year	Paper and venue	Question	Result
2007	Analysis of delivery reliability in power systems. ESREL, Stavanger	Can large complex systems be analysed without simplifying the models?	Splitting Markov models into unit models allows full-detail models of large systems, combined with load flow for different load, production, reserve and topology states.
2004	Analysis including reliability, income and cost for power systems. PMAPS, Iowa	Can reliability and its economic consequence be computed together for a real grid?	A model of about 6 million states replaced by 17 unit models; reliability, power flow and economic models combined on a Norwegian local grid.
2003	Economic benefits by use of the maintenance methodology function analysis and probabilistic methods in the primary and secondary system in high voltage installations. CIRED, Paris	What is the economic benefit of probabilistic methods in maintenance of primary and secondary equipment?	Full text not reviewed for this paper.

Table 3

Related: Svendsen (2002), master thesis, NTNU; Rausand and Høyland (2004), System Reliability Theory, 2nd ed., section 8.8; the 2007 Doble presentation on maintenance planning and control-centre use; Svendsen and Aabø, NEF Technical Meeting 2014, online risk management of the power system.

Lesson. The publications were written as the work happened, by the people doing it. They give an independent, dated trail for each claim in WP1–WP3.

9. Recognition and Independent Positioning

An independent EU review in 2014 identified Promaps Online as an existing commercial online risk tool, and the only one known to its authors that calculated interruption cost. National and European awards followed from 2014 to 2025.

9.1 GARPUR state-of-the-art review (2014)

The EU FP7 project GARPUR (2013–2017) developed probabilistic reliability principles for European TSOs. Its deliverable D1.1, *State of the art on reliability assessment in power systems* (lead: SINTEF Energi, March 2014), reviewed online security tools. It found that the dynamic security tools in use were deterministic, and pointed to Promaps Online as a commercially developed online risk tool based on Markov models with the Kronecker product. It stated that, to the authors' knowledge, Promaps Online was the only commercial online security tool calculating interruption cost.

Lesson. By 2014 the work was visible as a reference point in European research on probabilistic reliability, independent of its own publications.

9.2 Awards and nominations

Year	Recognition	Awarded by
2025	Winner, Grid Award "Good Practice of the Year 2025"	Renewables Grid Initiative, at the European Commission's PCI Energy Days
2017	Nominated, S.P.I.R. award for Promaps Realtime (national prize for climate technology and renewable energy)	S.P.I.R.
2017	Finalist, "Norway's Smartest Industrial Enterprise 2017" (Promaps Realtime)	Norsk Industri / Siemens
2014	Nominated, "Norway's Smartest Industrial Enterprise 2014" (Promaps Online)	Norsk Industri / Siemens
2014	Nominated, Norwegian Technology Award	Tekna

Table 4

The work has also been presented at the NEF Technical Meeting 2014 and the Recharge Leaders Thought Summit 2017.

10. Where We Stand Today

Today the method is documented, published, proven in live operation and recognised at European level. What has changed is the problem around it: grids are now the binding constraint on electrification, and the questions the early clients asked locally are now asked by the IEA and the European Commission at system scale.

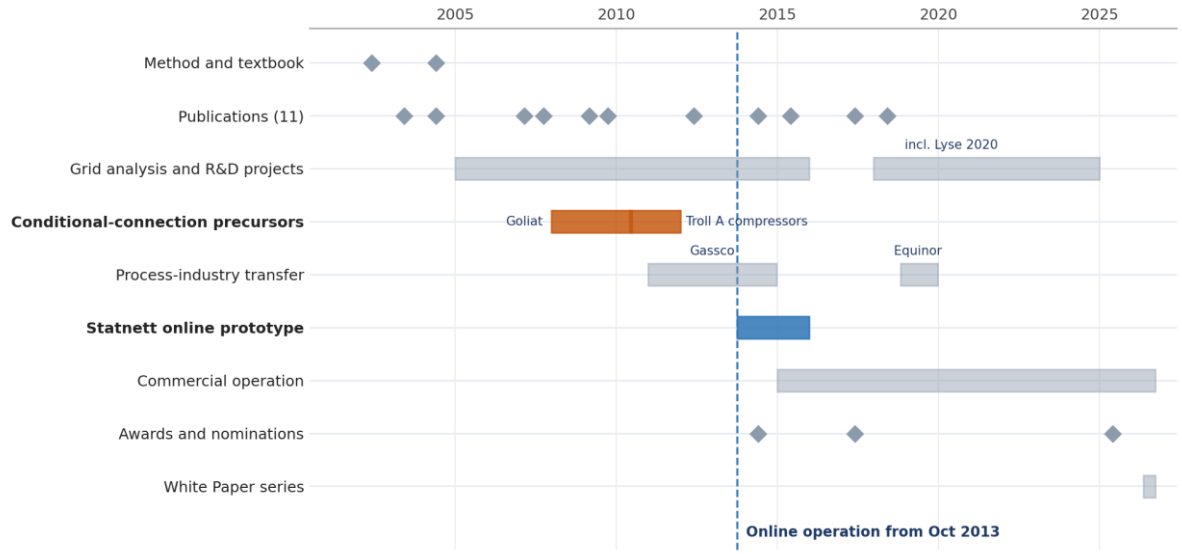


Figure 3. *Origins and operational record, 2001–2026. Method and textbook, publications, grid projects (including Lyse 2020), conditional-connection precursors (Goliat, Troll A compressors), transfer to process industry (Gassco, Equinor), the Statnett online prototype (from October 2013), commercial operation, recognition and the White Paper series.*

The timeline shows the shape of the journey: a method in 2002, a decade of projects, online operation from 2013, and commercial operation since 2015.

10.1 Lessons carried into the White Paper series

Lesson	Where it was learned	Where it is used
Probability, consequence and cost belong in one model	Master thesis 2002; PMAPS 2004	WP1 risk metrics (EENS, cost of energy not supplied)
A grid can pass the deterministic check and still lose regularity	Troll A 2008; ESREL 2009	WP2: N-1 has no probability and no consequence
Risk depends on operating state, reserves and weather	Landsnet 2005–2008; Doble 2007; weather projects / storm Tor 2013–2017	WP1 Decision Layer; dynamic rather than static margins
Operators need risk at one look	Statnett prototype 2007; ESREL 2014	WP1 Section 3.8, system-state representation
Online quantified risk allows operation beyond N-1	Statnett R&D; PMAPS 2012	WP2 Quantified N-1
Rising risk can be seen hours ahead	Møre 2014	WP1 early-warning use case
System redundancy can justify a simpler, cheaper design	National Grid 2008; Njarðvíkurheiði 2009	WP1 planning and investment implications
Large load can support security through curtailment or disconnection	Goliat 2008–2010; Kollsnes 2009; Troll A compressors 2010–2011	WP2 Virtual N-1; WP3 flexible loads
One model can serve operation, hindcast, maintenance and investment	Analysis services 2014–2020; Dalane 2018; Lyse Elnett 2020	WP1 common operational reference frame

Table 5

10.2 What did not go as planned

The record also contains setbacks. They are included because they show where the barriers were, and those barriers are the subject of WP1–WP3.

Funding. The first Statnett study (Sognenettet, 2005–2006) was planned with funding from Innovasjon Norge that was not granted; Statnett financed a reduced scope.

From prototype to permanent operation. The Statnett installation ran as an operational prototype from 2013 to 2015 but was not taken further into permanent control-centre operation. Commercial operation was instead built with regional and distribution operators from 2015.

Signed but not started. One signed leasing agreement from 2018 did not lead to installation because of resource constraints at the customer, and one planned test installation was not confirmed as operating. After a grid merger, operation continued only on part of the merged network (Section 7.2).

Documentation gaps. The full text of the 2007 Doble paper could not be located or opened when this paper was written.

Lesson. Where a reason is documented, the setbacks relate to funding, organisational capacity and the step from pilot to routine use rather than to the calculations themselves. That is the adoption barrier WP1–WP3 address (Section 11, conclusion 4).

10.3 What is new now

Three things have changed since the method was first put into operation. The scale of the problem has grown: connection queues and IEA estimates of 1,200–1,600 GW of latent capacity have made quantified risk a policy question (WP1). Computation has moved on: AI-based power flow solvers can evaluate operating states in milliseconds, which makes it possible to scale PRA and combine it with dynamic security assessment (WP1 Section 2.2). And large flexible loads such as data centres are arriving in volume, turning conditional connection from a special case into a general operating principle (WP2, WP3).

The core has not changed. The questions remain how likely a failure is, what it costs, and what an operator should do about it now.

11. Conclusions

The framework in WP1–WP3 is the result of 25 years of answering practical questions for grid owners, not a new proposal. Each of its main claims can be traced to a project, a publication or an operational observation documented in this paper.

Four conclusions follow from the record:

1. **The method works at scale.** Markov–Kronecker composition made full-detail reliability models of meshed grids tractable in 2002, and the same approach ran on Norway's national grid model in near real time from 2013.
2. **Deterministic N-1 hides risk in both directions.** Projects from Troll A in 2008 to Møre in 2014 showed grids that met deterministic criteria while their regularity was falling, and cases where quantified risk justified simpler, cheaper solutions than conservative rules would suggest.
3. **Conditional connection is proven practice.** Goliat documented in 2008–2010 that a large new load could be accepted with reduced or temporarily suspended land-power import as a corrective measure under constrained system conditions. In 2011, the licence for the Troll A compressors allowed connection ahead of grid reinforcements on condition of system protection and disconnection. Virtual N-1 generalises this principle with quantified risk as the trigger.
4. **The remaining challenge is adoption, not invention.** The technical capability has been demonstrated in operation. What remains is integration into TSO practice, common risk metrics and regulatory frameworks, which is the agenda of WP1–WP3.

WP0 will be updated as further installations, project details and operating years are documented.

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Appendix A. Project Register, 2005–2024

Year	Project	Client	Type	Section
2024	Kollsnes project	Equinor, Gassco, Statnett	Analysis	–
2021	Promaps maintenance module, internal development	Vysus Group	R&D	–
2020	Regularity analysis of Haugaland power system	Haugaland Kraft	Analysis	7.3
2020	Promaps Realtime–UNC / Utility Network interface and holistic risk-analysis R&D	Lyse Elnett	R&D	7.3
2019	OPRA Kårstø simulation, phase 2	Equinor	R&D	4.6
2018	OPRA Kårstø simulation update, phase 1	Equinor	R&D	4.6
2015	Online risk management with weather influence 2	StormGeo, RFF	R&D	6.4
2014	Regularity analysis of Møre power system	Statnett	Analysis	7.1
2014	Online risk management with weather influence 1	StormGeo, RFF	R&D	6.4
2014	OPRA overpressure risk analyser, phase 4	Gassco	R&D	4.6
2013	Reliability analysis, Steinsland transformer station	BKK Nett	Analysis	5.3
2013	Risk management of operation, phase 4	Statnett	R&D	6.2
2013	Risk management with real-time weather data	StormGeo, RFF	R&D	6.4
2013	Risk analysis of flare system 3	Gassco	R&D	4.6
2012	Risk management of value chain (PAS 55)	Statnett	Analysis	5.3
2012	Risk analysis of flare system 2	Gassco	R&D	4.6
2011	Risk management of operation, phase 2	Statnett	R&D	6.2
2011	Risk analysis of flare system	Gassco	R&D	4.6
2010–2011	Compressors 3 and 4 for Troll A	Statoil	Analysis	4.5
2010	Risk management of operation, phase 1	Statnett	R&D	6.2
2009	Optimal risk-based substation design, Njarðvíkurheiði	Landsnet	R&D	5.2
2009	Risk management of operation, pre-project	Statnett	R&D	6.2
2008–2009	Single-sided supply of Kollsnes	StatoilHydro	Analysis	4.4
2008	Station design reliability assessment	National Grid UK	R&D	5.1
2008	Alternative load point to Troll A	StatoilHydro	Analysis	4.2
2008–2010	Electrification of Goliat FPSO from Hammerfest	Eni	Analysis	4.1
2007–2008	Integrated reliability model	Landsnet	R&D	3.3
2007	Electrification of Troll A from Kollsnes	StatoilHydro	Analysis	4.2
2007	North Iceland 132 kV system	Landsnet	R&D	3.2

Year	Project	Client	Type	Section
2007	Risk management in operation, western Norway	Statnett	R&D	6.1
2006	Lutelandet to Gjøa platform	SFE	Analysis	4.1
2006–2007	West Iceland 220 kV system	Landsnet	R&D	3.2
2005	East Iceland 132 kV system, Kárahnjúkar	Landsnet	R&D	3.2
2005–2006	Sognenettet	Statnett	R&D	3.1

Table 6