Power system developments and mathematical challenges

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OUTLINE

Introduction: DNV GL, R&I Energy, myself,
Power systems: developments, complexity, uncertainty
Example projects: (more) math to power systems
Challenges and questions

Industry consolidation

DNV

GL Group

KEMA

NOBLE DENTON

GARRAD HASSAN

ADVANTICA

In a challenging world we make businesses better prepared

Global reach – local competence – committed to innovation

- **Investing 5% of our revenue in research and innovation**
- **Collaborating with industry partners and external experts**
- **Sharing knowledge through standards and recommended practices**
- **Providing foresight and initiate competence building and innovation**

150+ years	**350** offices	**100** countries	**13,000** empl.

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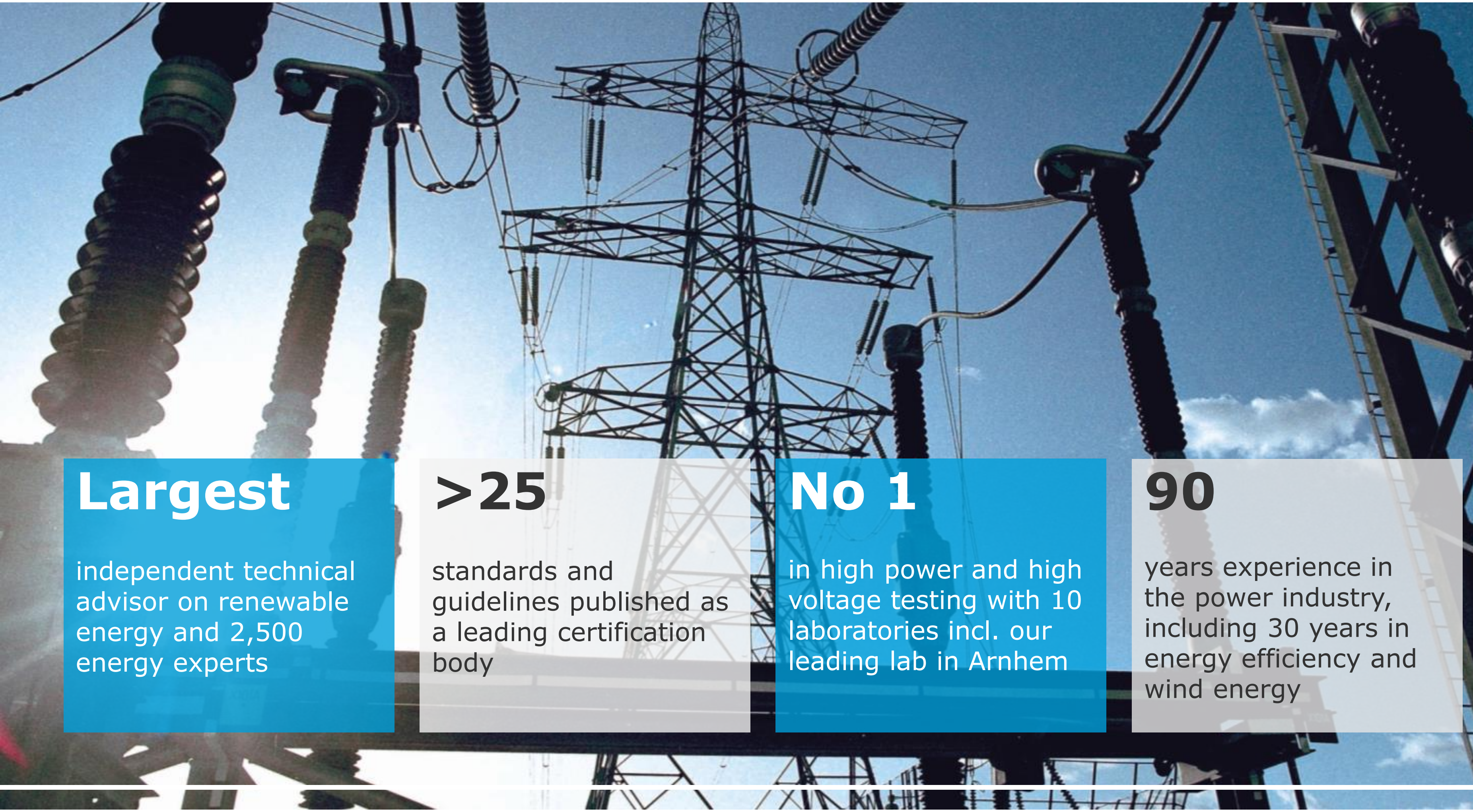
An energy technology powerhouse



Largest

independent technical advisor on renewable energy and 2,500 energy experts

>25

standards and guidelines published as a leading certification body

No 1

in high power and high voltage testing with 10 laboratories incl. our leading lab in Arnhem

90

years experience in the power industry, including 30 years in energy efficiency and wind energy

Power chain and DNVGL services

Policy → Production → Transmission & distribution → Use

- Power testing, inspections and certification
- Renewables advisory services
- Renewables certification
- Electricity transmission and distribution

- Smart grids and smart cities
- Energy market and policy design
- Energy management and operations services
- Energy efficiency services
- Software

Seven strategic research and innovation programs

OIL & GAS AND ENERGY SYSTEMS
- Offshore safety
- Safety and reliability of the subsea factory
- Energy foresight

CLIMATE CHANGE
- Adaptation
- Renewable energy
- Green economy
- Transformation process

HEALTHCARE
- Patient safety

INFORMATION TECHNOLOGY
- Autonomous systems
- Big data analytics of sensor data

POWER & RENEWABLES
- **Renewables**
- **Grid transition**
- **Power Cybernetics**

MARITIME TRANSPORT
- Safer shipping
- Greener shipping
- Smarter shipping

MATERIALS
- Materials in energy storage
- Risk management of corrodible systems
- Advanced materials and sensors

About me

- 1982 MSc. Applied mathematics, Operations Research, UTwente, Enschede, NL
  - reliability of electricity distribution systems
- Joined 1986 KEMA, many roles and topics
  - Researcher, consultant, simulation software developer, systems administrator, works council, serious games moderator, trainer of professionals, supervising students, … , …
  - Reliability, (Dutch national) Outage registration, Network optimization, Innovation, "Socket at Sea", Smart Grids, GrowDERs EU-project, storage, dispersed generation, Modeling/Simulation/Gaming, regulation, transition of energy infrastructure, stochastic grid analysis, Super Grids, HVDC control, …
- 2013 Transfer to DNVGL Strategic Research & innovation
  - Bridging gap between power systems experts and mathematicians
  - Contribute to several research projects and PhD work
  - Position papers

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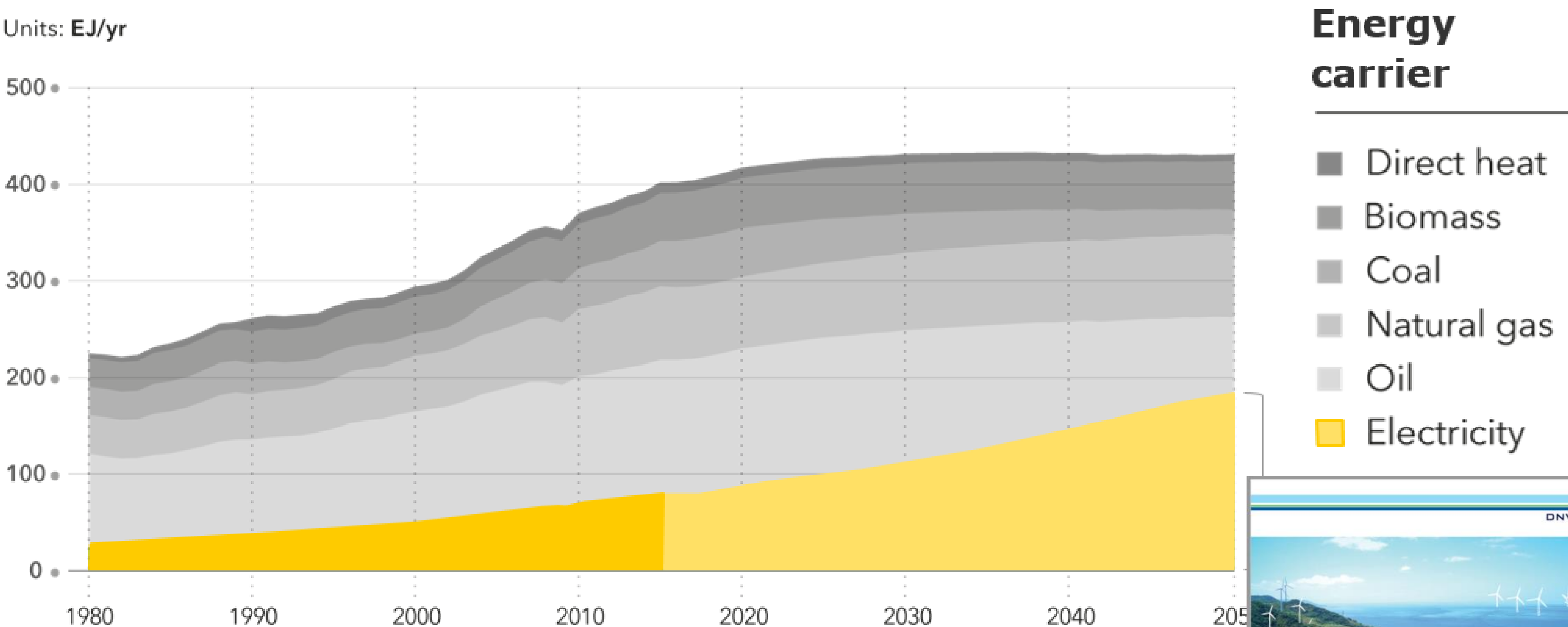
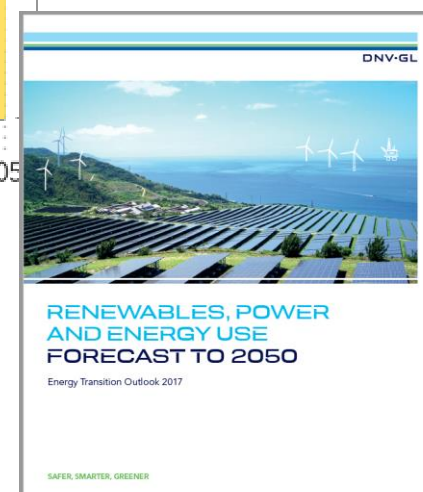
Power grids - complexity and developments

tips of icebergs – no formulas

SAFER, SMARTER, GREENER

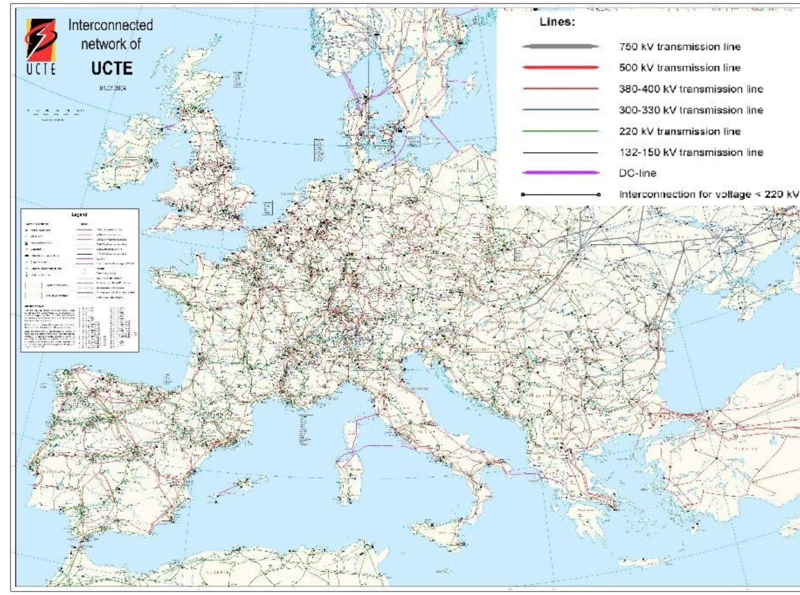
The world is electrifying...



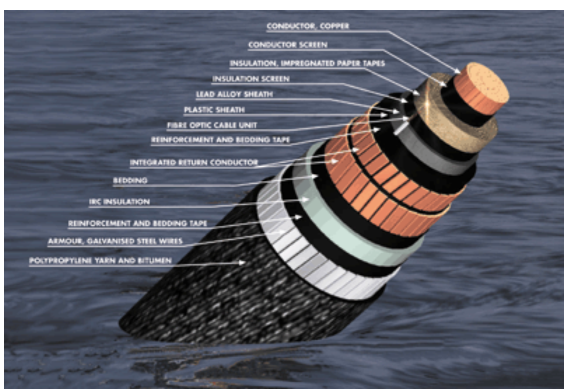


- Energy Transition Outlook
  - https://eto.dnvgl.com/2017/

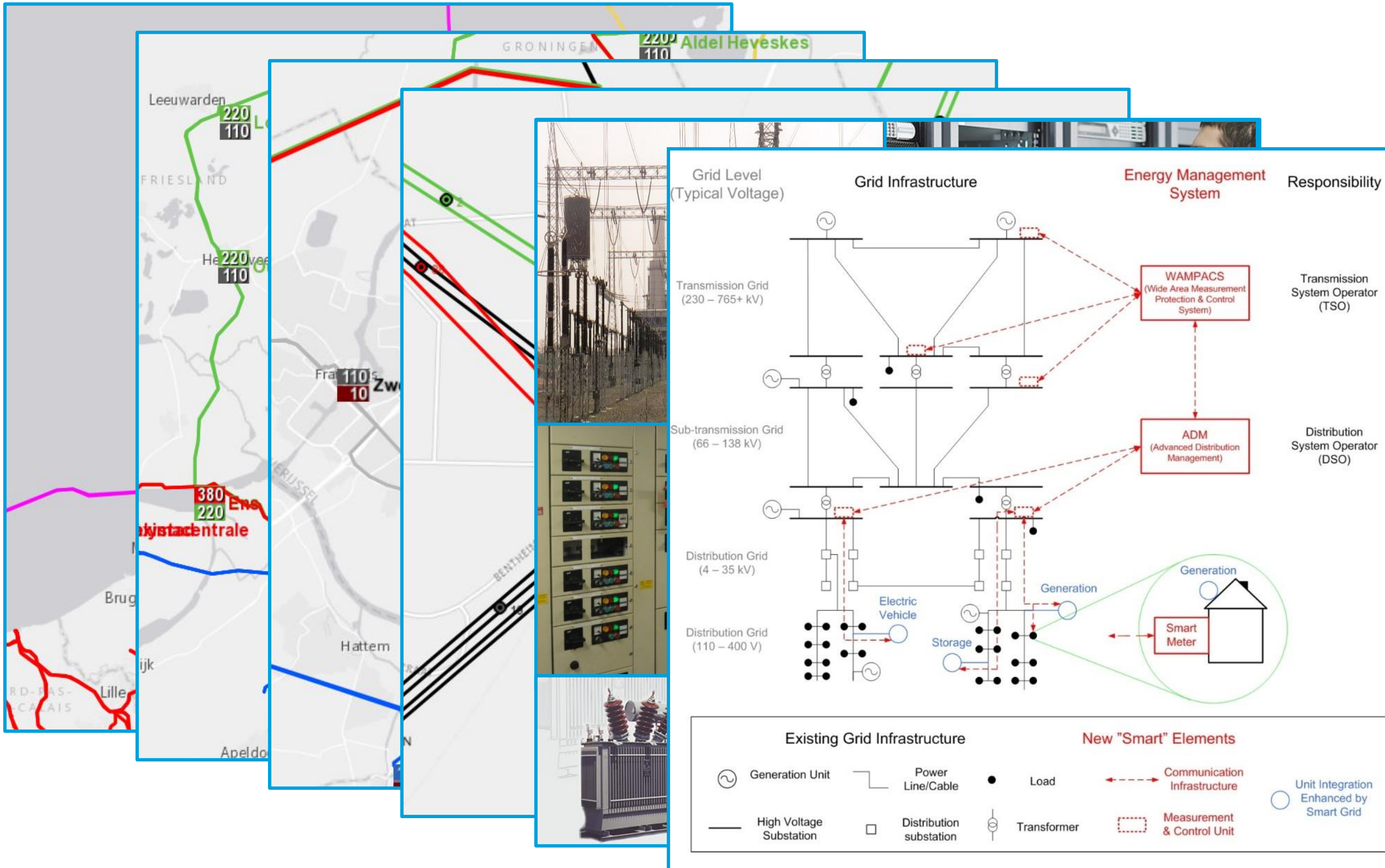
The electric power system, infrastructure



- The electrical network consists of layers with different voltage levels
  - high voltage: transmission (EHV, UHV)
  - medium voltage
  - low voltage: distribution
- There are different network operators
  - With a regulated monopoly
- Networks:
  - nodes (substations)
  - connections (transformers, lines or cables)



Grids are complex … … and are evolving



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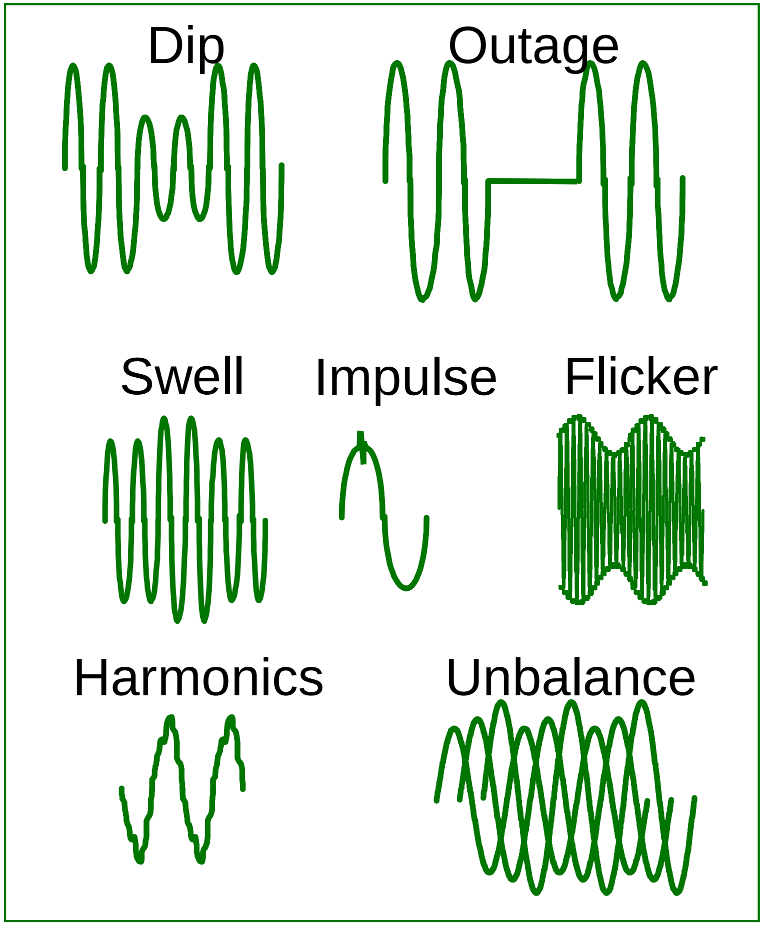
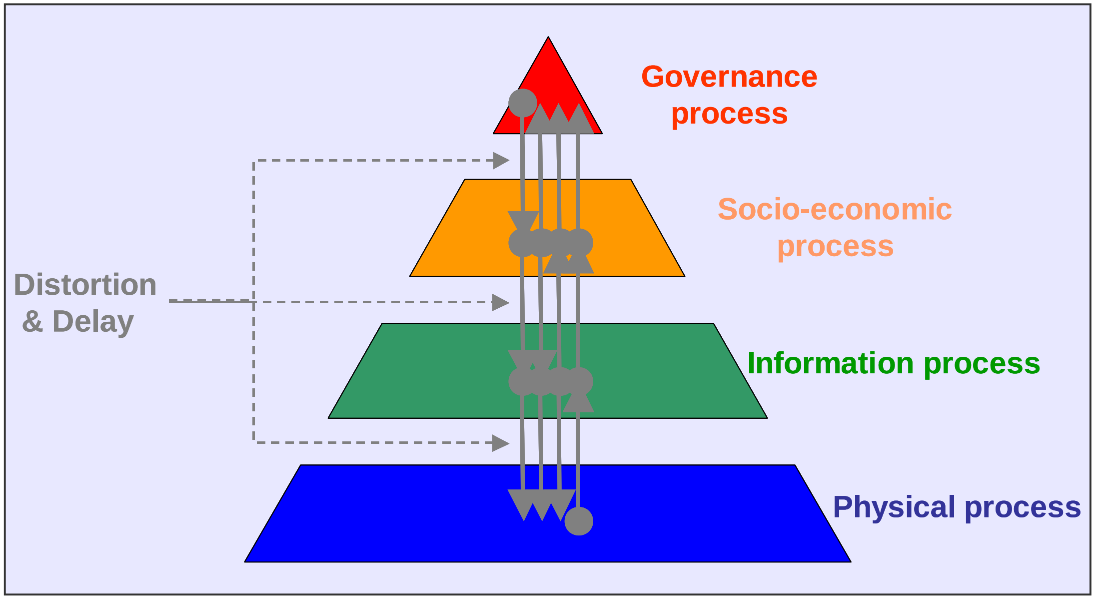
Complexity Scope – beyond 3-phase 50 Hz sinus
Quality of supply

- (un-)Availability of supply (interruptions)
  - Frequency (SAIFI)
  - Duration of outages (CAIDI)
  - Customer minutes lost (CML)
- Voltage Quality
  - According to EN 50160
  - Voltage dips, harmonics, flickr, voltage variations, asymmetry, overvoltages, others
- Service quality



Complex organization, overall many stakeholders



Liberalised markets
- Generating companies
- Households
- Industries
- Energy Traders and Retailers
- Power Exchange (like APX)
- Local and central government
- …

Regulated Monopoly
- Regulator
- Transmission System Operator (TSO)
- Distribution Network operators (DNO or DSO)

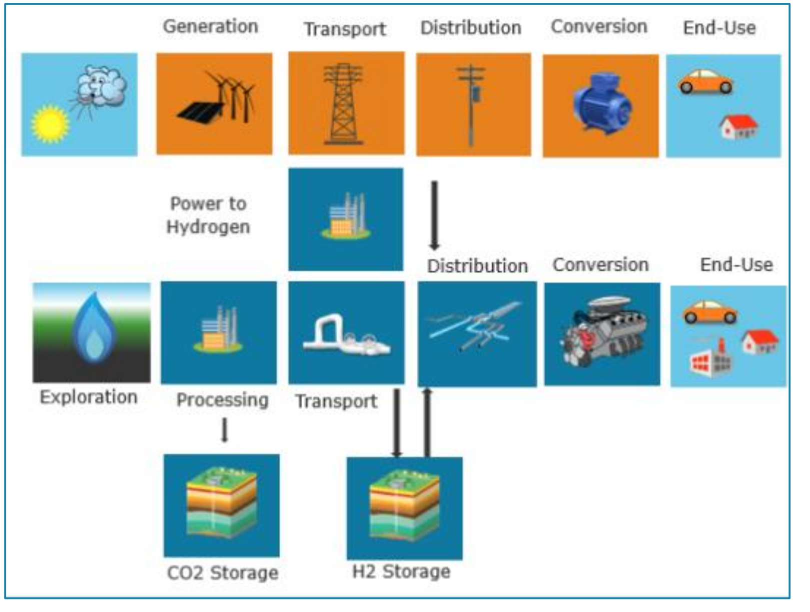
New stakeholders: new power equipment, new appliances, new services, …
- Manufacturers
- IT-companies
- Aggregators (energy, flexibility, …)
- Financial parties
- …

Complexity when integrated with other infrastructures

- Infrastructures are interdependent, substitutable or competing (heat, gas, …)
- Electricity supplies most other infrastructures (e.g. water, IT, rail, traffic, …)
  - And power grids depend on some as well, like IT
- Many conversions possible (direct or as storage)
  - Heat pumps, heat storage, compressed air, gravity (hydro), …
  - Power-to-Gas, Gas-to-power, (CH_4, H_2),
  - Vehicle-to-grid, Grid-to-Vehicle

And we know non-public grids:
- ✓ industrial grids
- ✓ office area's, microgrids
- ✓ inside installations (e.g. data hotels)
- ✓ marine vessels (civil & other)
- ✓ offshore, sub-sea(bed), …

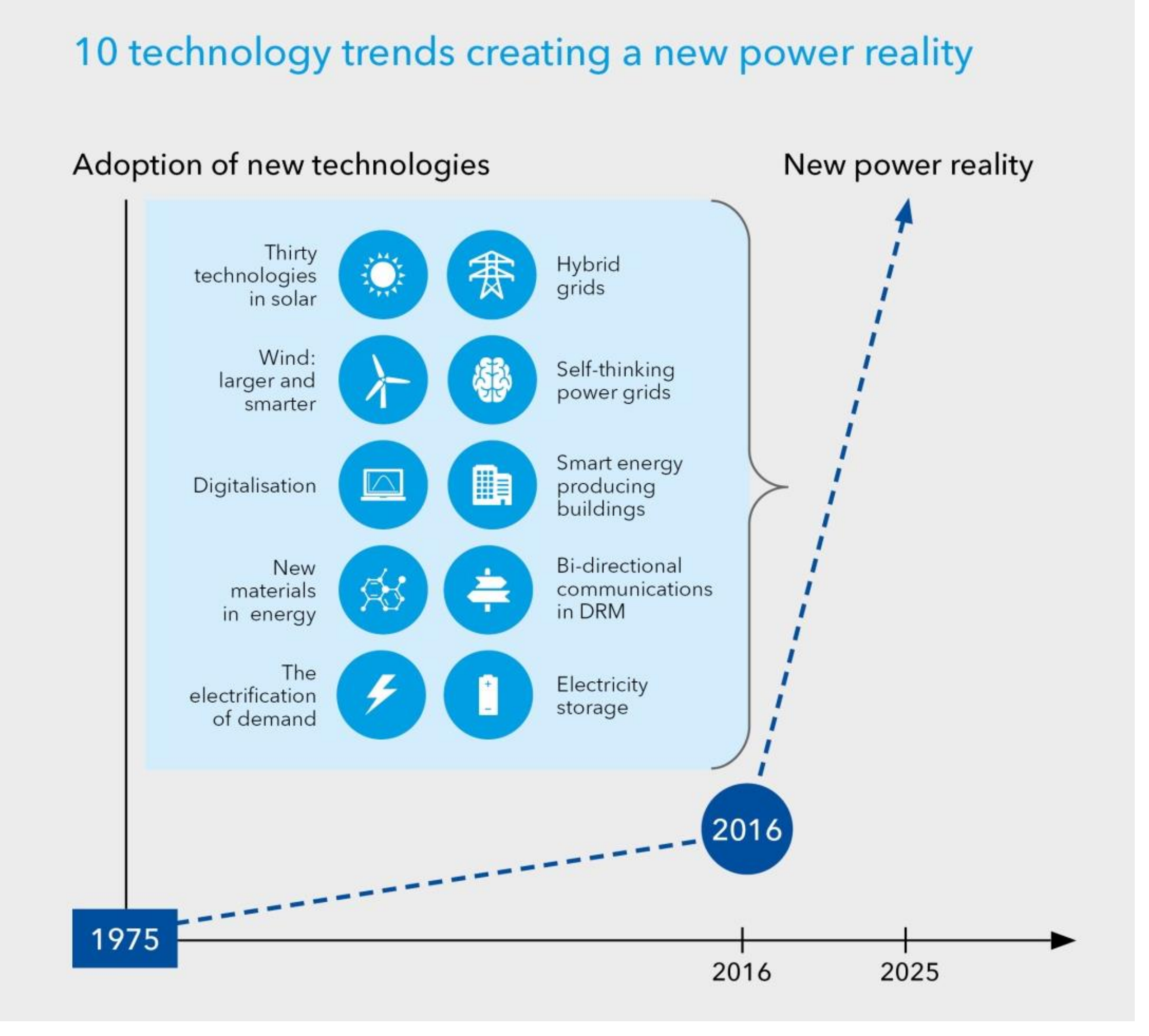
Mathematically all similar ☺



Timescales (power ≠ energy)

- Decades, years
  - Investment planning, Regulation
  - Transition to sustainable energy world?
- Months, weeks
  - Maintenance scheduling
  - Seasonal storage operations
- Days, hours, minutes
  - Markets
  - Operations, dispatch, switching
- Seconds, milliseconds
  - Automation, control, protection,
- Milliseconds
  - Failure effects, control, …

Technology outlook slide:
10 technology trends creating a new power reality



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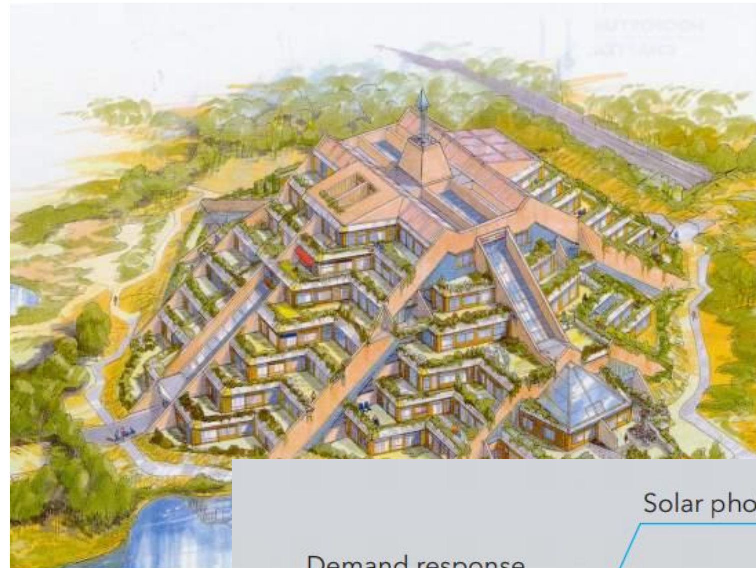
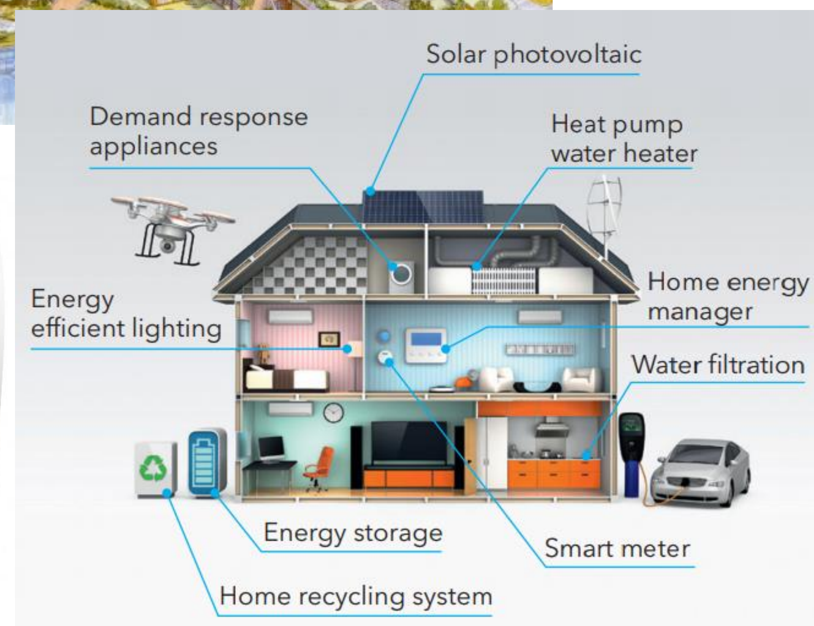
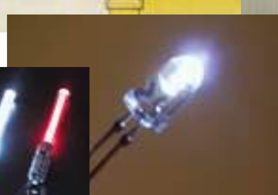
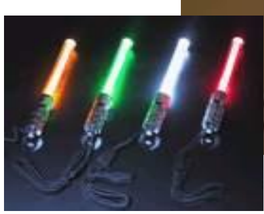
13 January, 2018

Houses become more sustainable









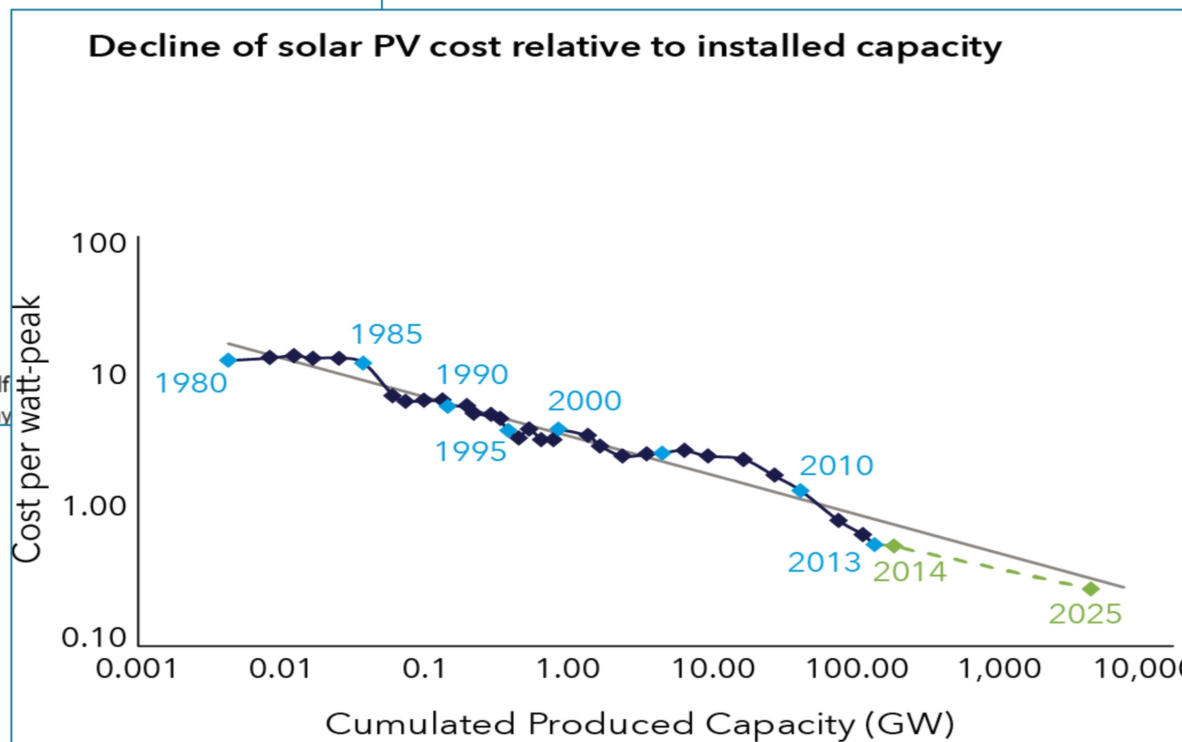
Developments in solar PV will drive down costs (and increase use)


News

First »subsidy-free« solar power plant in Great Britain officially opened

Post date: 26/09/2017 - 17:11

The 10-megawatt Clayhill solar power plant near Flitwick (Bedf
yesterday. The plant, developed by renewable energy company



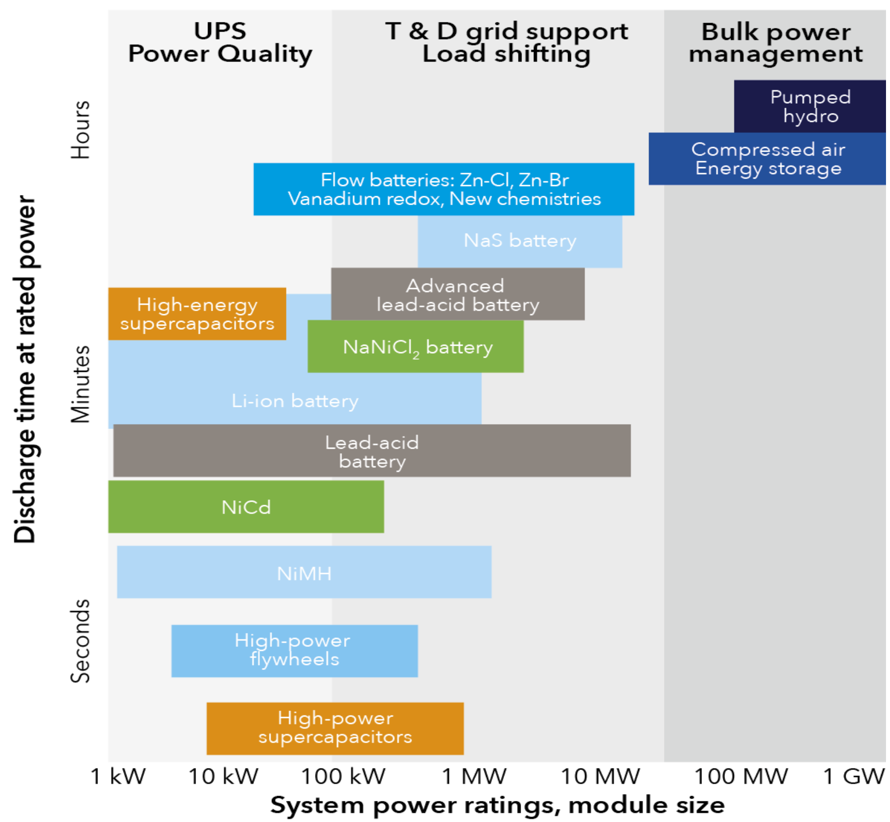
Electricity storage for three discharge durations

Applications require storage of various duration, favouring different technologies

Expected decline in battery prices suggests that home storage will grow rapidly

Renewables - a key driver for upscaling of energy storage

Application range for alternative energy storage technologies



Wind: larger and smarter

By 2025 onshore wind will be the least-cost option for building excess electricity capacity almost universally

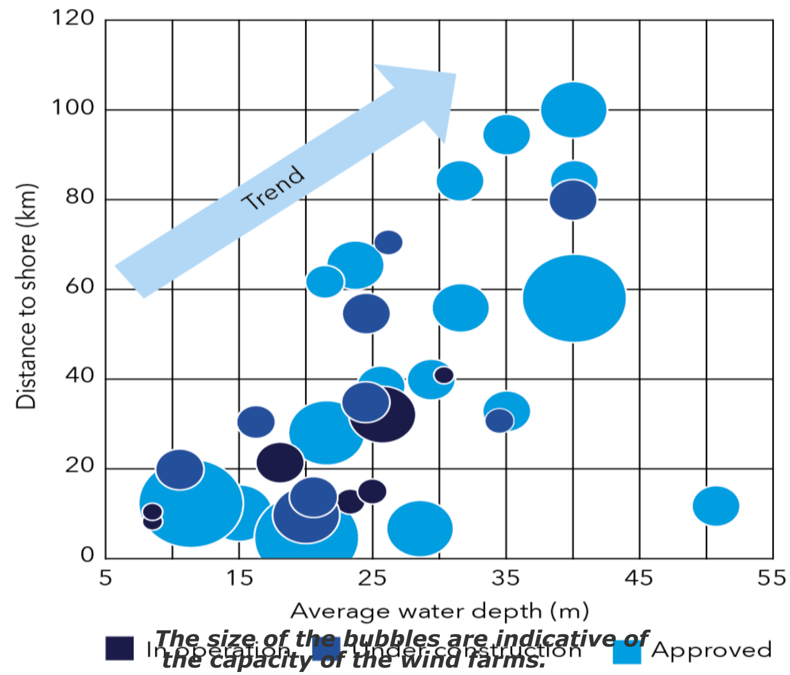
Fixed offshore wind moves towards deeper waters, further from shore

Floating offshore wind is entering demonstration phase

Breakthrough 'zero bid'

For two projects – OWP West and Borkum Riffgrund West 2 – DONG Energy made bids at **zero EUR per MWh**, i.e. these projects will not receive a subsidy on top of the wholesale electricity price.
http://www.dongenergy.com/en/media/newsroom/news/articles/dong-energy-awarded-three-german-offshore-wind-projects

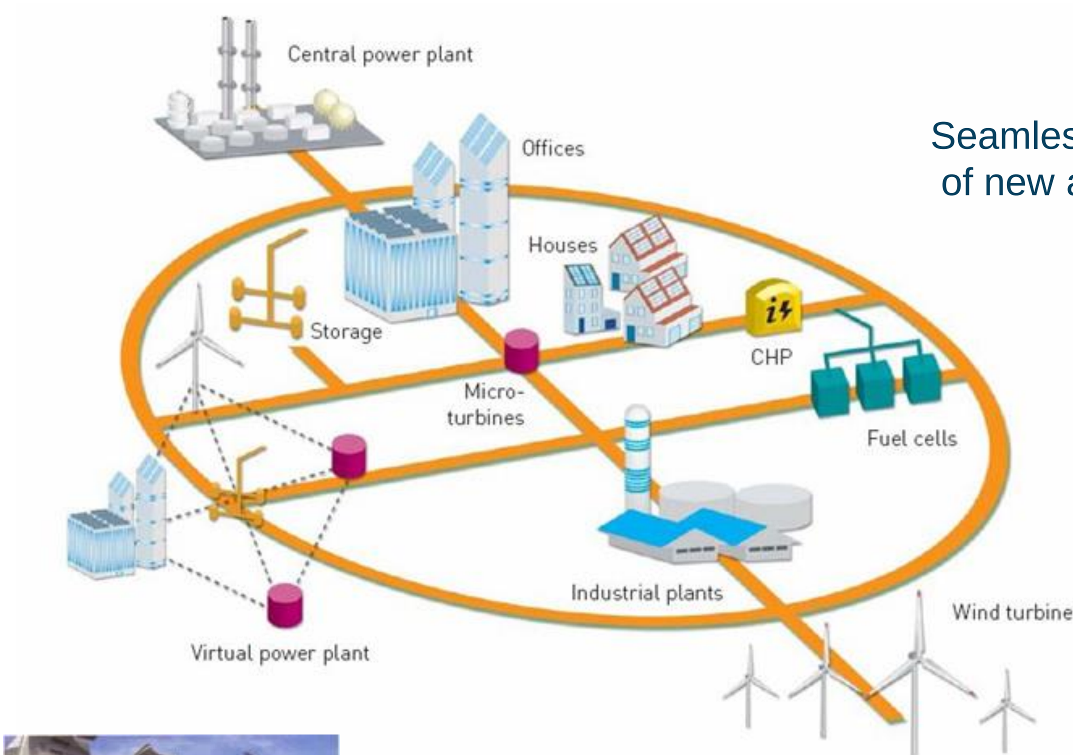
Distance to shore and average water depth of a representative selection of European wind farms. The size of the bubbles are indicative of the capacity of the wind farms.



The size of the bubbles are indicative of the capacity of the wind farms.

A more Internet-like power grid emerges (next to IoT)

Customer real time
Information & participation



Seamless integration
of new applications

Central & dispersed
intelligence

Smart power
electronics

Central & Dispersed sources

Large-scale energy storage.

PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

- Artificial island in North Sea
- Store wind powered hydro energy

Our contribution

- Initiate project and set up partnership structure
- Feasibility study

New developments TenneT, Gasunie, ao

- Spoke & hub at Doggerbank

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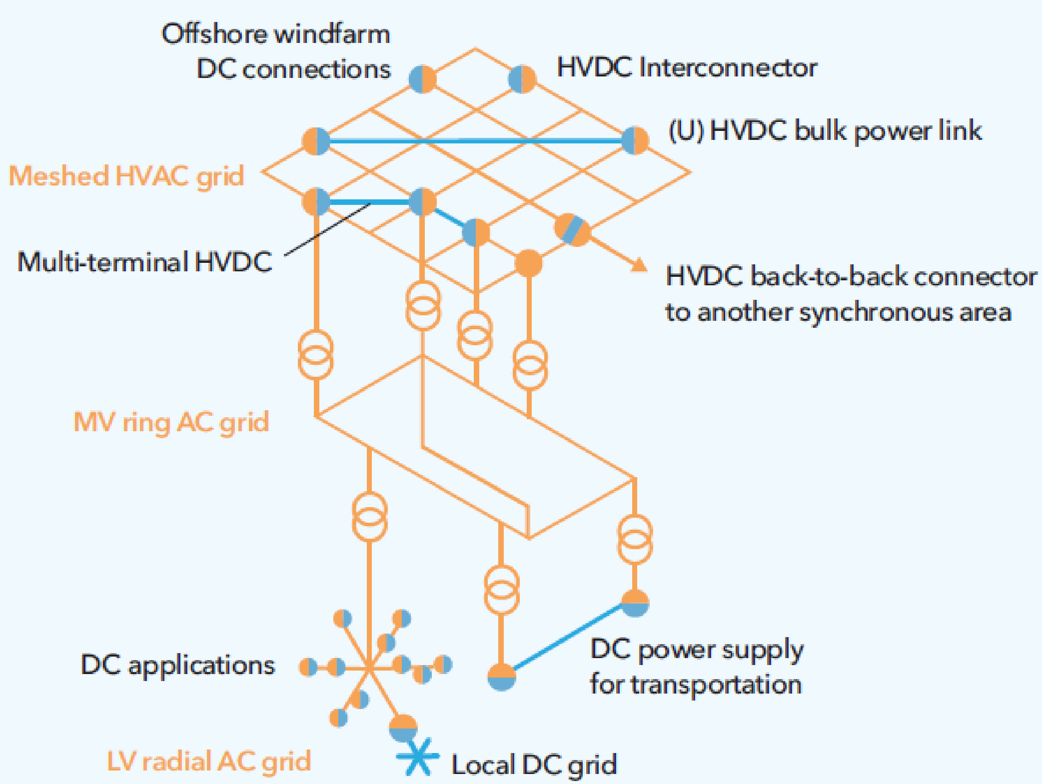
Opportunity: Hybrid grids

FUTURE POWER SYSTEM GRID ARCHITECTURE – AC+DC HYBRIDIZATION (FIGURE 4-9)



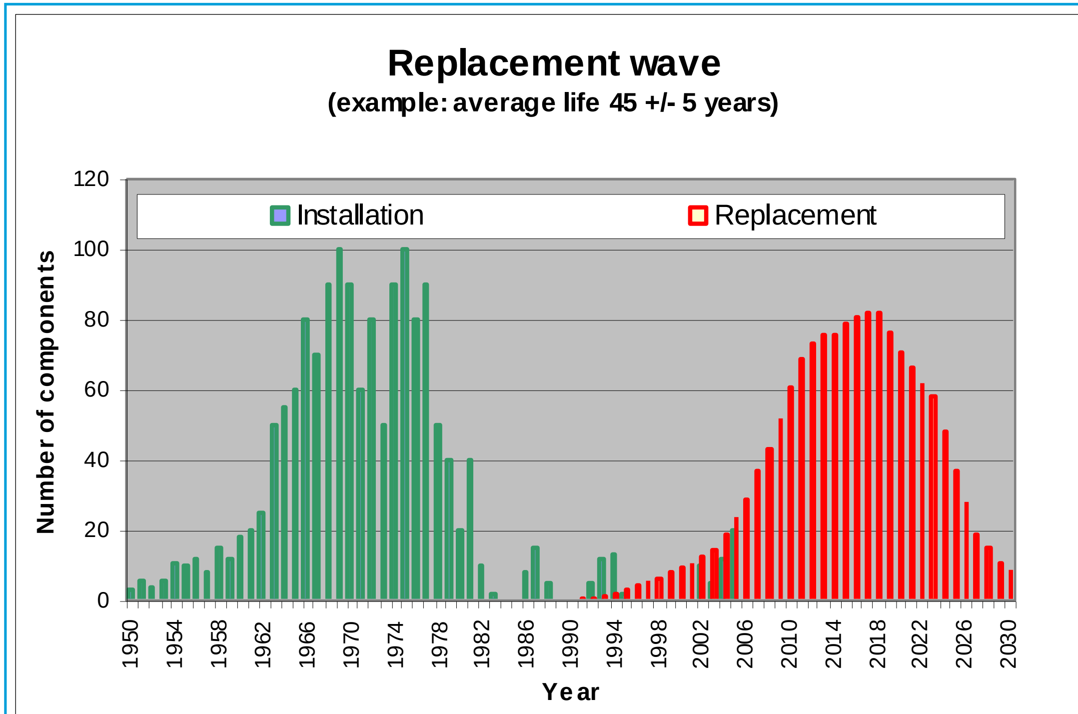
Abbreviations

AC	Alternating current
DC	Direct current
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
LV	Low-voltage
MV	Medium-voltage
(U) HVDC	Ultra-high-voltage direct current

Challenge: replacement wave
(planning for) large scale renewal of aging equipment

- Massive deployment of equipment during 60's and 70's
- Estimated lifetime 40-50 year
- Threats:
  - Budget
  - Aging workforce
  - Scarce materials

- Uncertainty
  - 1-1 replacement (40 yr) or innovation?



Other interesting developments

- Demand side response, demand side management (agent technology?)
- More data available, but ownership scattered
- Climate change remedial actions (?)

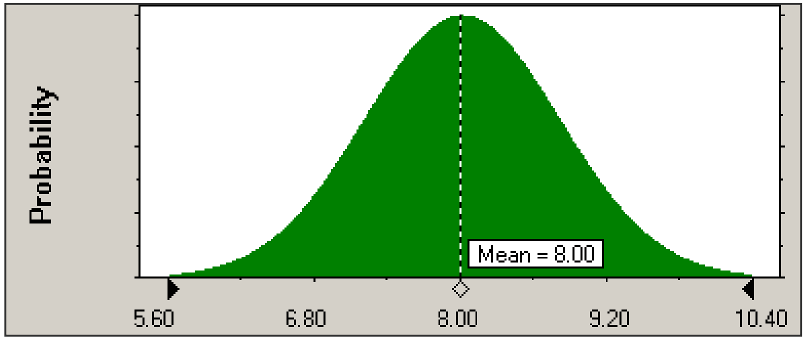
- Changing regulation or still non-existing
  - Fairness and/or liability issues

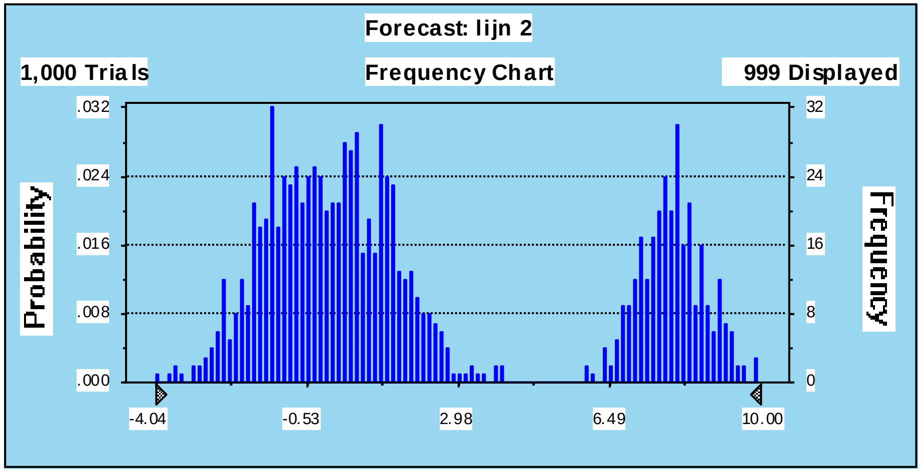
- Dilemmas between free market for energy trading and monopolies for grid
  - **Self organising criticality**, smaller margins
  - Increasing N-1 / N-2 violations (from annual to daily)

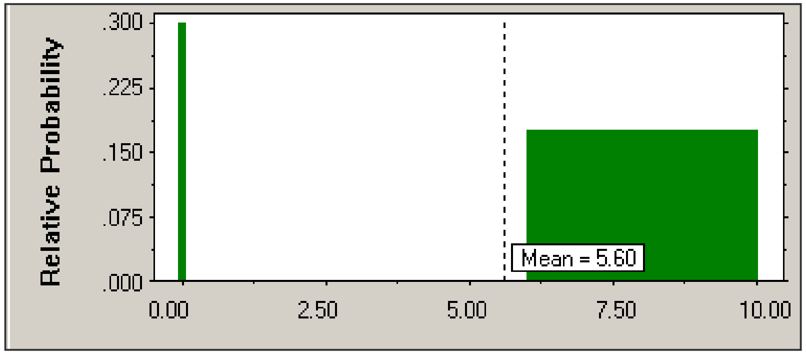
Examples of projects and studies

Dealing with uncertainty: Probabilistic loadflow.

- Input = measurement / assumption of distributions of a large number of quantities.
- Calculation = simulation of a large number of different combinations of input values (Monte Carlo).
- Output = distribution of all quantities, including worst-cases, correlations and risks.

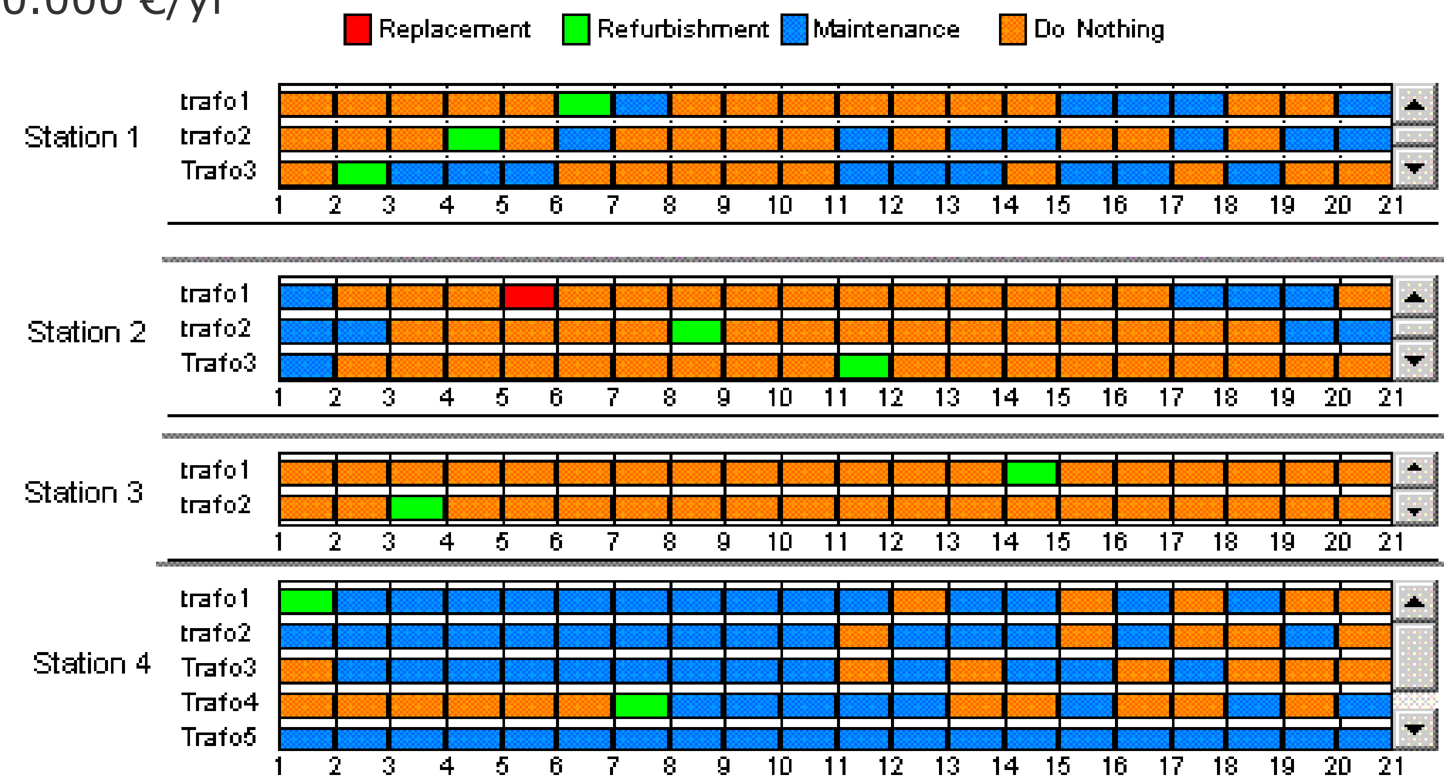






Optimizing constrained transformer replacement / maintenance / inspection / no action

- Different objectives and constraints per station are possible.
- Mixed integer non-lineair problem. Solved in AIMMS. Combination of non-linair and mixed integer solver. Embedded reliability model.
- Client saved 300.000 €/yr



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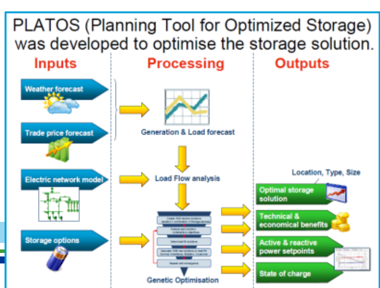
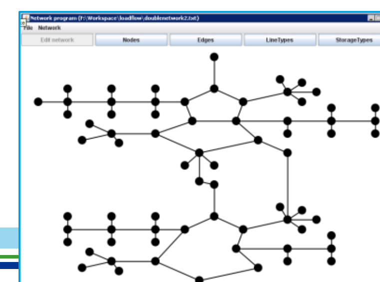
Storage optimisation, find optimal number and locations of storage units, for grid congestion and/or trading

- Engineering approach
- Bottom up approach
  - Close to business-as-usual
  - Familiar loadflow
  - New storage element
  - Assumptions for storage control
  - Repeat as needed (*heuristic*)
- Nice grid pictures
  - Easy to explain
- Stuck in combinatorial swamp
  - No full optimisation possible
- Useful for “easy” problems

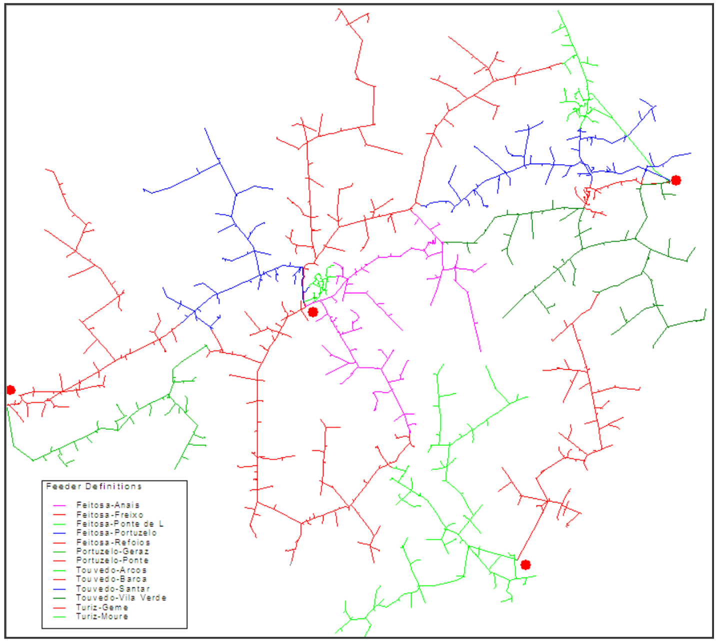
- Computing Science master
  - Uni Utrecht Stephan Leemhuis
- Formulate as optimisation problem
  - Integer linear program
  - Focus on objective and constraints
  - Assumptions for the rest
- Use of (math) library
  - LP solvers
  - Simulated annealing, local search
- Much faster solutions (**> 10 000 x**)
- Optimal storage control: bonus result
- “academic style” tool

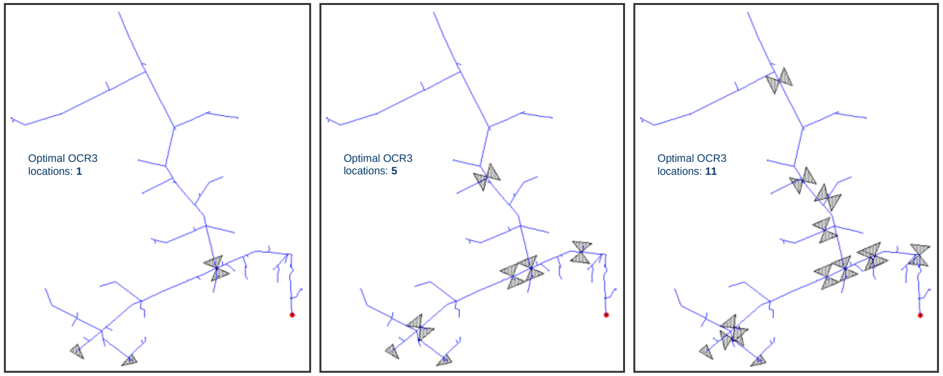


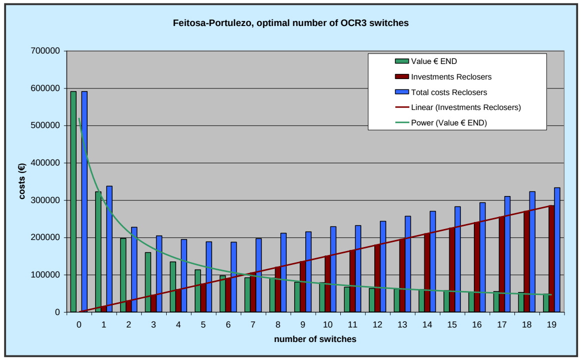


KEMA Optimal Location of Distribution Automation
Alternative validation by KEMA

- Application of Genetic Algorithm
  (model: Genodal, “full optimisation”, contrasted with heuristic model in Excel)
  - Based on PowerFactory, scripts for the genetic algorithm
  - 99% guaranteed optimum, calculates > 1.000.000 solutions
  - Result to Excel for portfolio







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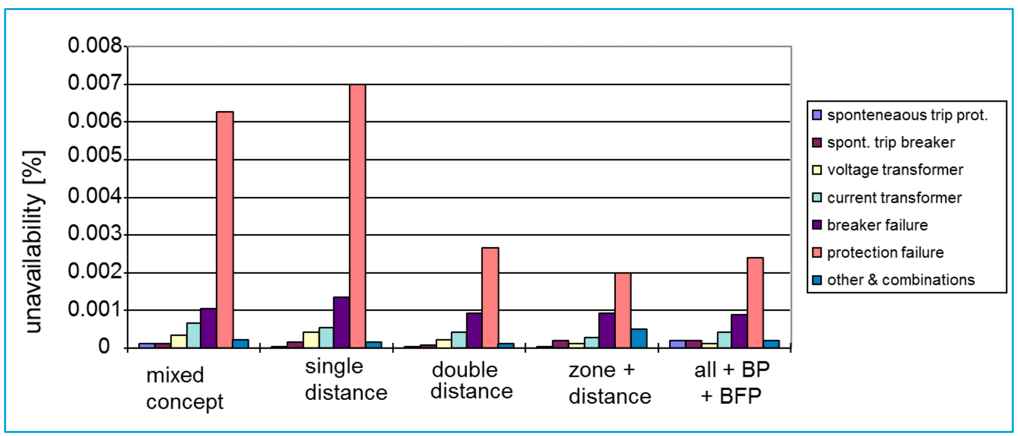
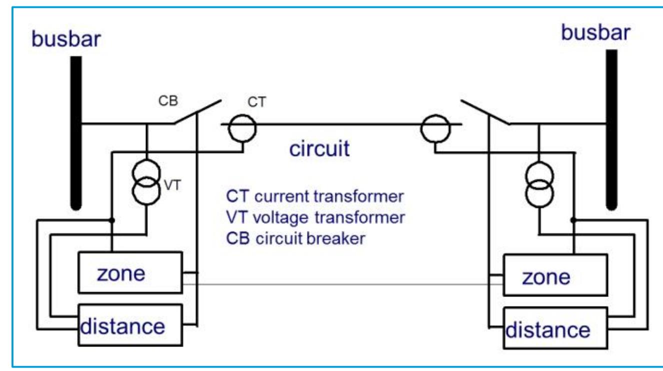
Technology innovation: Power Electronics

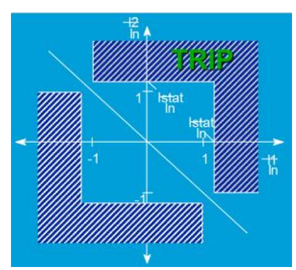
- Innovative new Power Quality laboratory
- Hardware in the loop testing
- Control hardware in the loop testing
  - Combine virtual and real things
  - Validate new algorithms/controls
  - Develop new regulation or standards
    - Challenge: chicken-and-egg

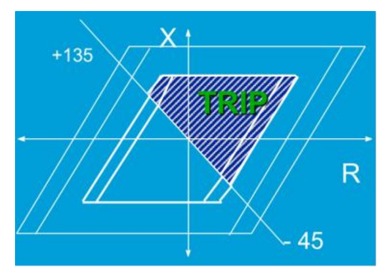
ProRank, Protection Reliability Analysis

- Calculating grid reliability, including detailed <u>modelling of protections systems</u>
- Distinguishes sensors, relays, breakers, telecom, individual settings
  - Required a lot of detailed input data
- Based on discrete event combined with short circuit calculations
  - long mtbfs' combined with short protection times
- Next:
  - ?? Protection (was) not (yet) significant
  - Things may have changed a lot (1999)









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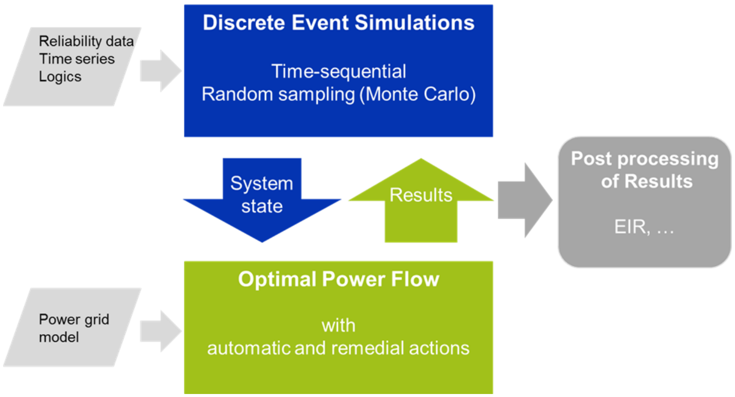
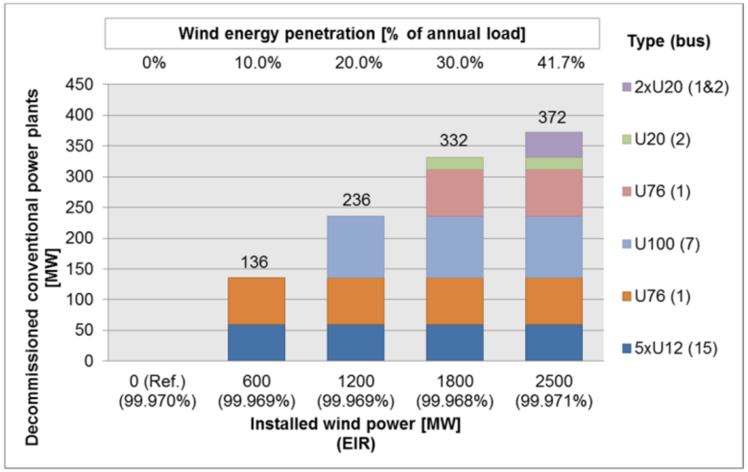
PoweRisk

- Quantify wind power contribution to system adequacy
- Aimed at offshore HVDC
- Discrete event and Optimal Power flow
  - combination of existing tools, extended

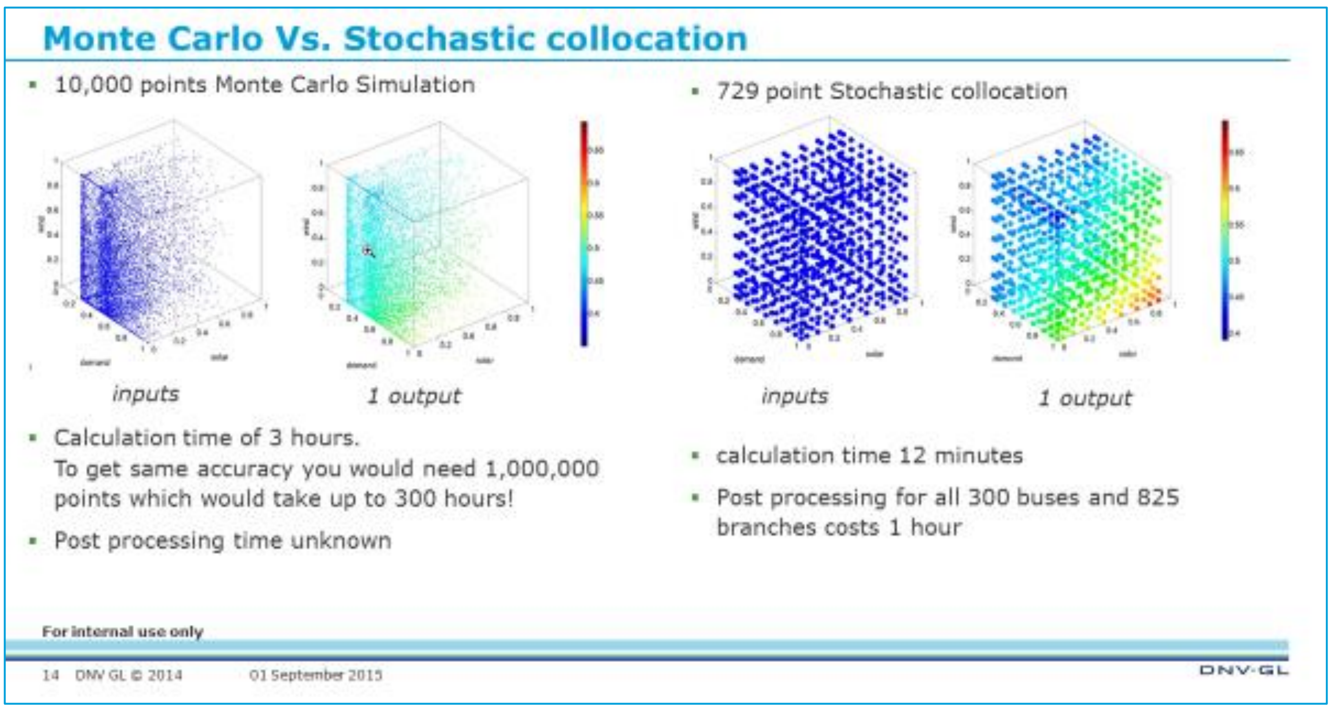
- Next, add:
  - ramping limits
  - transient behaviour





Stochflow
(CWI cooperation, Jeroen Witteveen)

- Grid analysis with stochastic wind generation
- Application of Stochastic collocation, combined with “standard” loadflow PSS/E
- Results for (all) indices as distributions (comply with brute MC)
- Proof of principle succeeded, dimensionality challenge not yet solved



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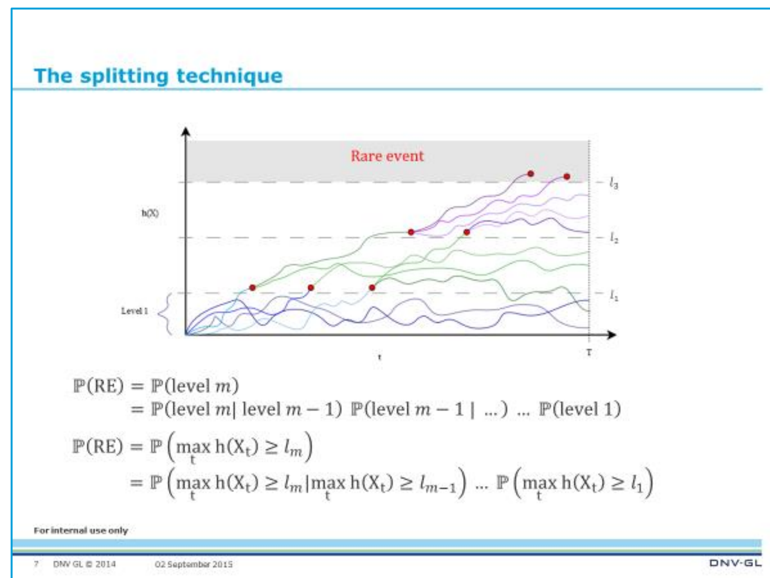
Splitting, speeding Monte Carlo
(CWI, PhD study, Wander Wadman)

- Rare event simulation
- Applied to transmission grid with wind generation, aimed at finding probabilities of overloading
- Power-injections: Ornstein-Uhlenbeck process, assumes DC power flows

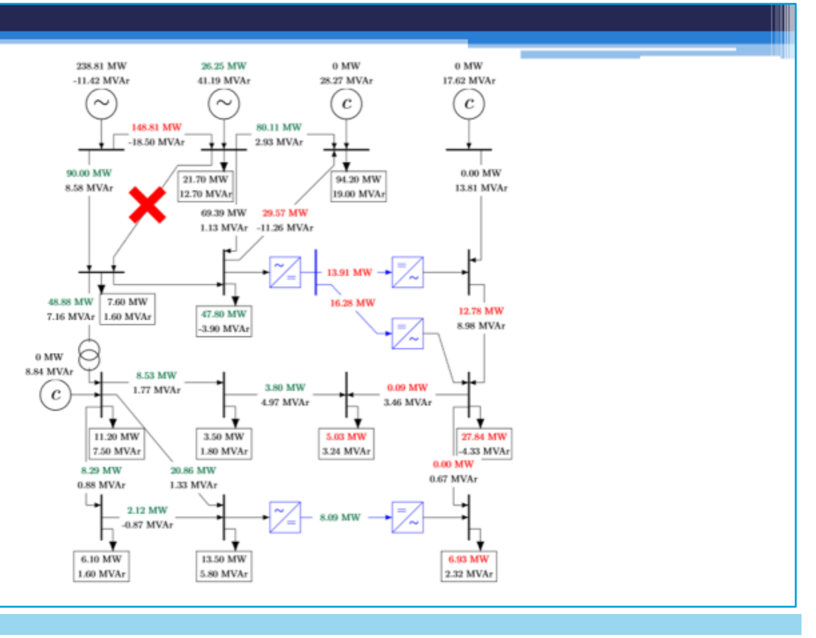
- Outperforms Crude Monte Carlo by far, computationally efficient
- Critical in choice of importance function

- Next:
  - Apply to real grids? Pilot-project?
  - Include component outages?
  - Large Deviation based importance function?
  - AC power flow?



Optimizing VSC setpoints for embedded HVDC power systems
(master, Uni Utrecht, Joost Linthorst)

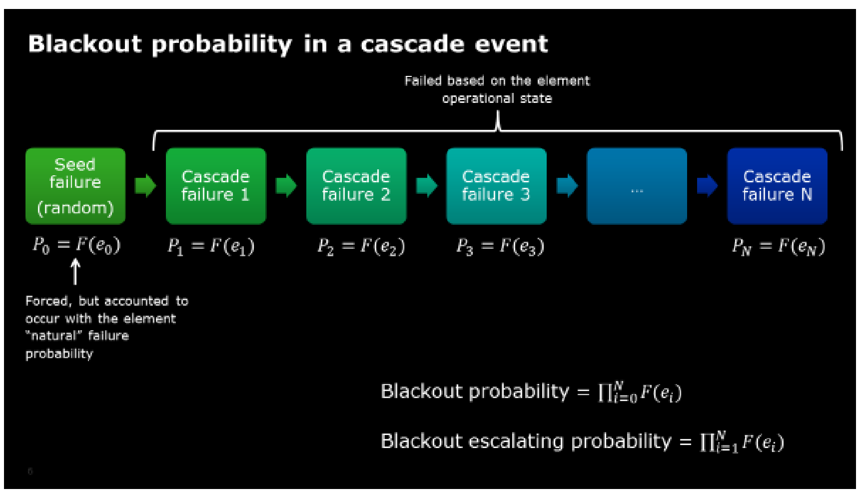
- Optimising controls of embedded HVDC systems
  - Embedded: more than point-to-point, risk of loop-flows
  - Capable of handling large amounts of HVDC
- Flexible in choice of objectives, e.g. loss-minimisation, back-up power supply
- Used MATACDC and non-linear solver IPOPT-solver with add-ons, linear approximations, custom made genetic algorithm
- Proof-of principle succeeded
- Needs finetuning and practical tests
- Next:
  - Speed up?
  - Add topology options?
  - Add DC-droop (time changes)
  - …

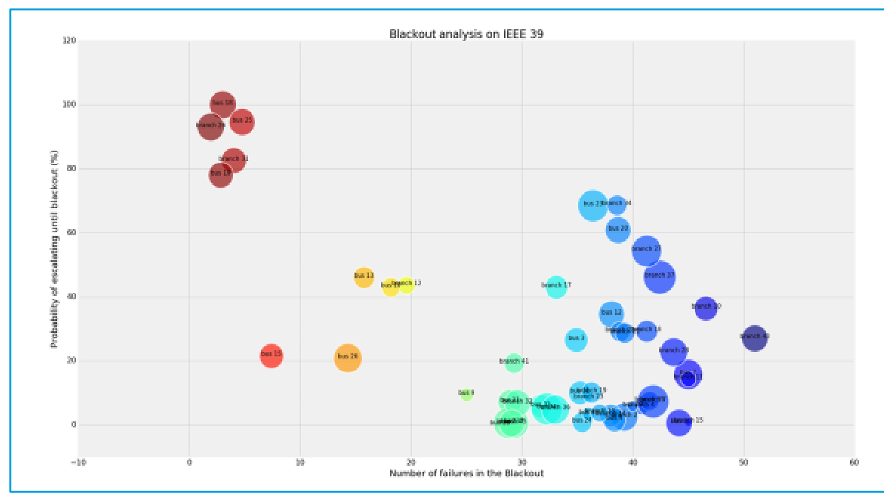


Black-out estimator

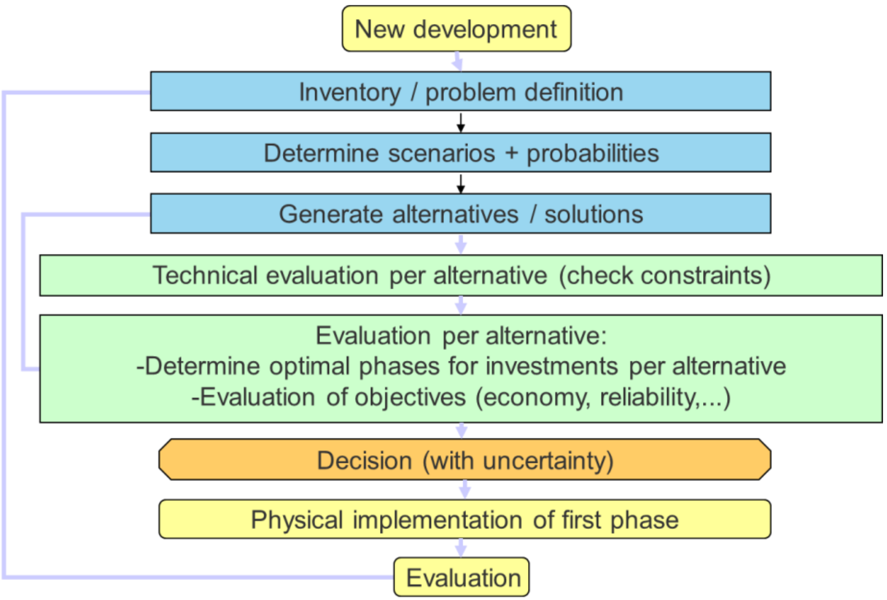
- Looking for cascading (high order) failures, based on grid conditions
- Pseudo splitting order, based on loadflow results first, then probabilities
- Very robust new loadflow HELM (holistic embedded loadflow method)
- Scales roughly linearly (not exponential)
- Better than N-1, more insight in criticalities of components

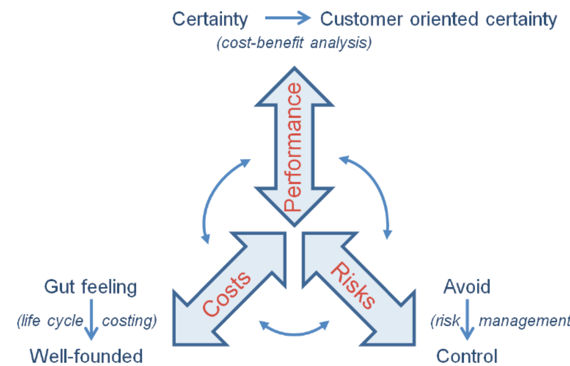
- To be investigated: completeness of method

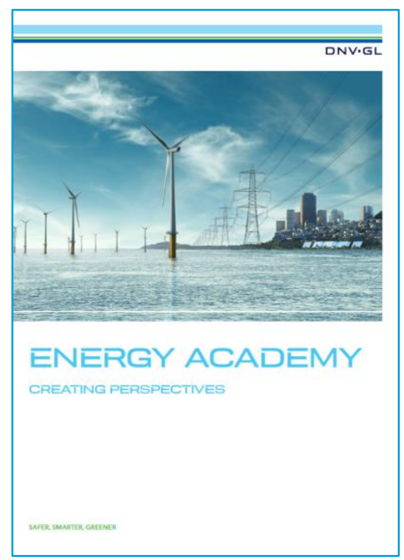


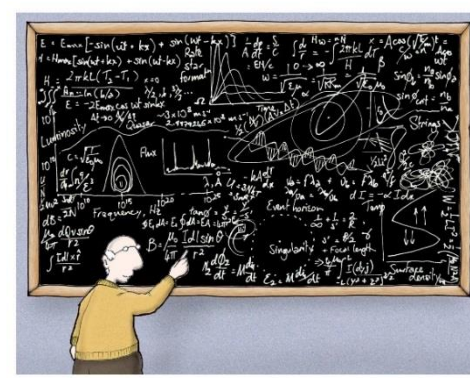


Training *Decision making with uncertainty*
Serious Gaming *FleXnet*



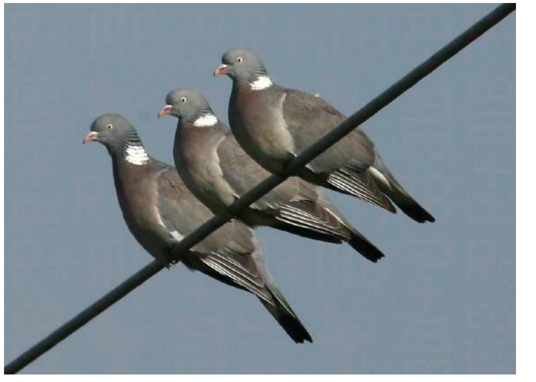






Development / Challenge: Dynamic monitoring

- Current state-of-the art: monitor cables individually
  - Using optical fibre in cores or other sensors
  - Not really predictive, acting real-time
  - Re-dispatch by operator or pre-sets
- Next step: transformers



Challenge:

- Multiple components, gridwise (system)
- Automated switching (within all constraints)
  - Needs detailed criticality models of components
  - Needs state estimation for network & predictions
  - Needs fast network calculations
- Optimisation problem

Predicting remaining lifetime is a related issue, need for more data and more models

Other ideas or opportunities

- Identify contributing components to grid distortion (PQ)
  - Given Power Quality measurements in the grid,
  - Based on "fingerprints" and other data

- Given maintenance history of assets, predict remaining lifetime
  - for different scenario's?
  - to support decisions in asset management (short term) or grid planning (long)
  - Optimise replacement planning, what/when, like-for-like or smart(er)

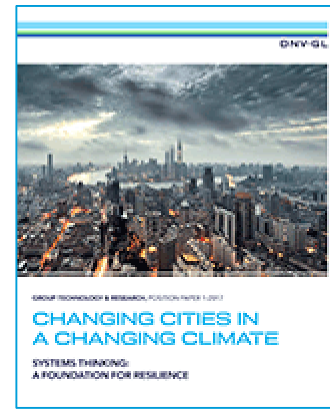
- Optimising overall protection in smart grids or super grids
  - DC controls (HVDC or home grid)
  - Maybe fast "islanding" and local solutions? (and preconditions)

Interchange or re-combine objectives & constraints
- Re-consider philosophies to support transitions
- Needs math as objective means for stakeholder effects

Uncertainties and complexity increase, so does urgency

- Society is depending on a reliable, affordable and clean energy infrastructure
- In the electric power systems there are a lot of uncertainties
  - Some uncertainties are inherent, some are solvable
- Pressure for innovation is omnipresent
  - Acting as usual is a guarantee for an increase in problems
- For many uncertainties there are developments even uncertain themselves, they can be seen as a challenge
- The complexity is increasing enormously
- The “usual” computational tools are insufficient

- Pilots and past projects demonstrate the potential of “new” methods



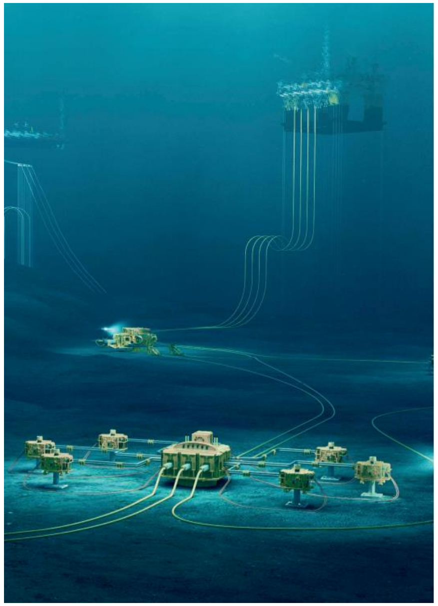
Conclusion:

There is a need for more math / mathematicians in the energy industry

Challenges and questions 1/2

- How to decide under uncertainty, taking care of:
  - Multiple objectives, multiple stakeholders (new entrants and incumbents)
  - Multiple timescales
  - Market versus grid (economy vs physics)
  - Multiple infra's

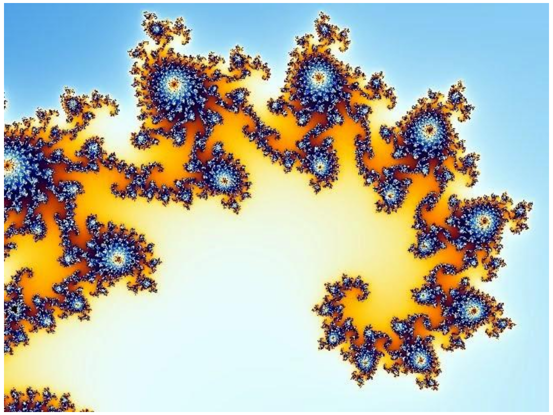
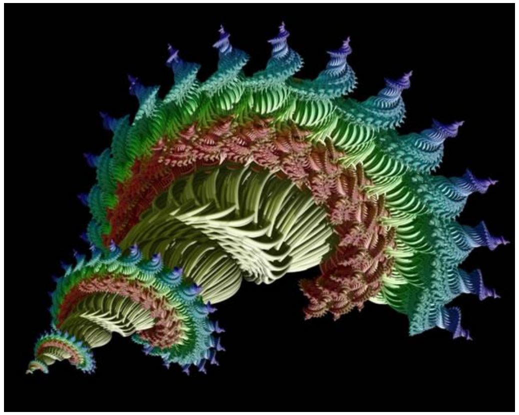
- Find adequate approximations (zoom in/out, fractal like)
  - Integrate disciplines, provide consistency,
  - use toolbox approach



Challenges and questions 2/2

- Is there a meta-problem: how to set regulations and policies ?
  - How to address “fairness”
  - Can dual solutions be of help?
- Educate (all) stakeholders, increase transparency
  - How to trust decisions, despite uncertainties and complexity

- How to close the gap between research and applications?
  - Proven methods may well be enough to start with
  - In theory, practice and theory are the same, but in practice …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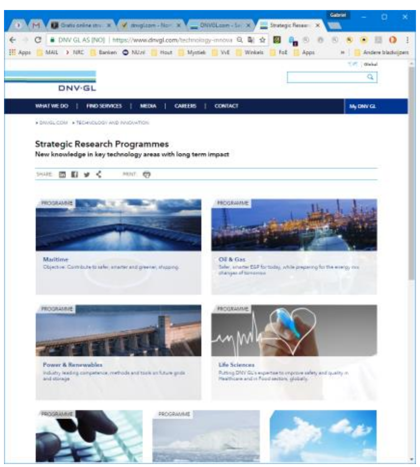
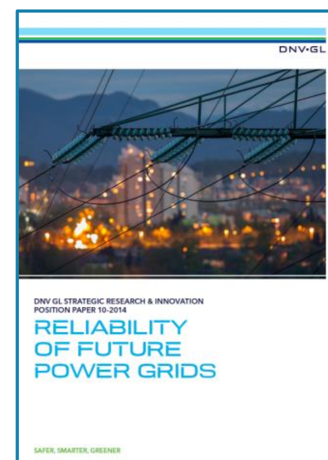
Collaboration

- Beyond proof-of-principles on demo or toy-problems, we need:
  - **Integrated** solutions (math, physics, economics, legislation)
  - **Realistic** examples for relevant stakeholders
  - **Robust** consistent tools and data definitions
- DNV GL can collaborate in several ways
  - Support new proposals, support master projects and PhD projects
  - Support part time professors
  - Work on implementation, e.g. hiring postdoc's
  - Work on pilot projects
  - Do testing or demonstration in laboratories
- Of course conditions apply ☺

Typical references https://www.dnvgl.com/ and

- Position Paper: Reliability of Future grids
  - https://www.dnvgl.com/publications/reliability-of-future-power-grids-18950
- Technology Outlook 2025
  - https://to2025.dnvgl.com/
- Energy Transition Outlook
  - https://eto.dnvgl.com/2017/





Suggestions, questions, proposals, ...

please contact:

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