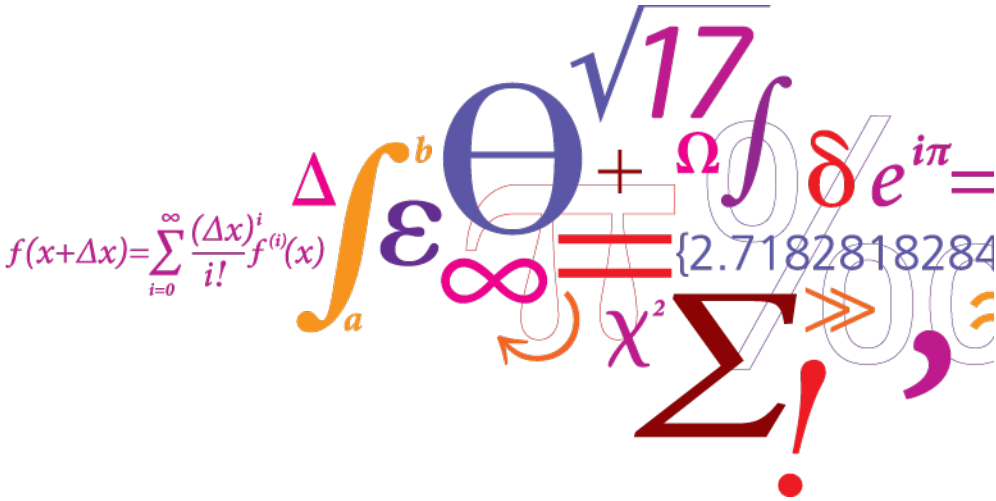
MULTI-DC
Controlling the power flows

Spyros Chatzivasileiadis
Assistant Professor

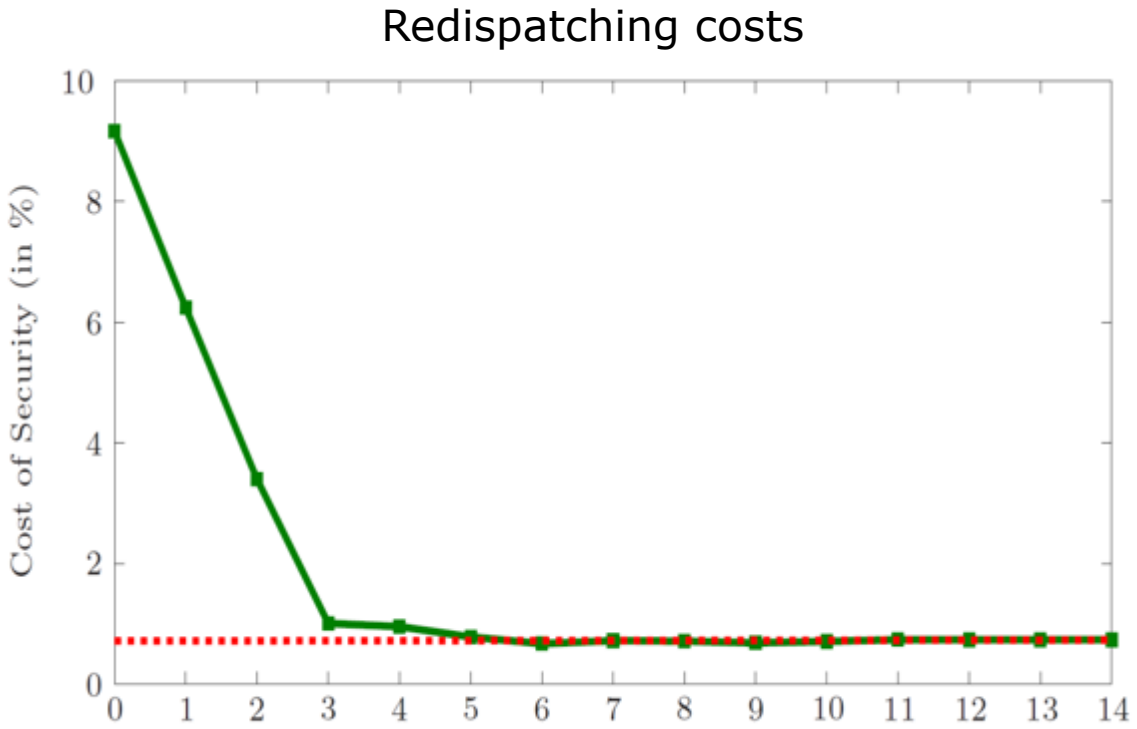
Videnscafe, Energinet
2 October 2017



Center for Electric Power and Energy
Department of Electrical Engineering

Vision:
Towards a fully controllable power system

- Decouple "completely" the market operations from the security considerations
- Fully controllable power flows eliminate redispatching costs
- Ensure secure operation and market-optimal dispatch
- HVDC, FACTS, flexible demand



Few FACTS devices sufficient to eliminate redispatching costs

Chatzivasileiadis, Andersson, A Fully Controllable Power System-Concept for FACTS and HVDC Placement, https://arxiv.org/pdf/1506.08250.pdf

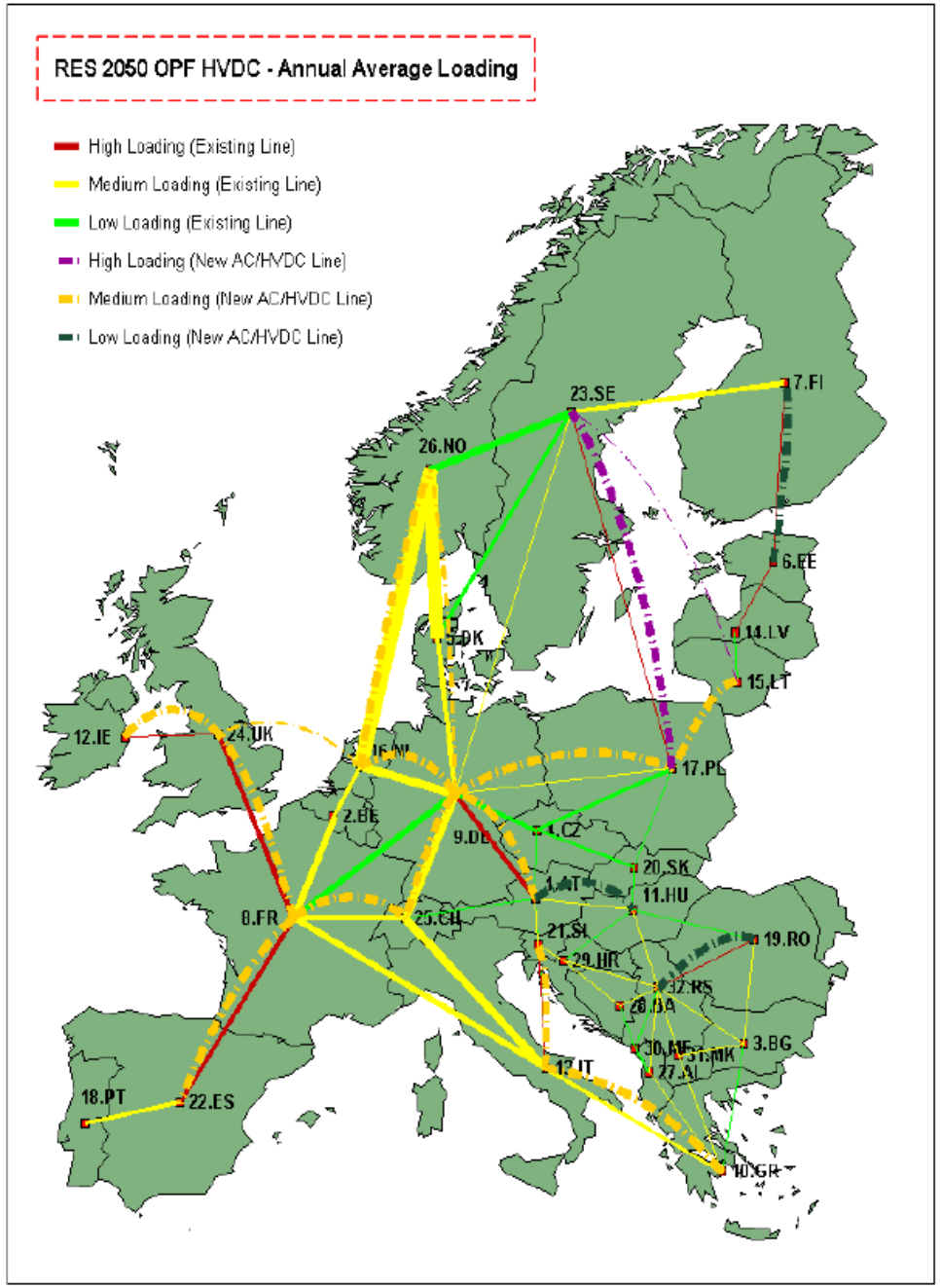
Towards a European Supergrid

Scenario: 80% RES by 2050

Simplified European System

Three options:

1. AC-400 kV
2. AC-750 kV
3. HVDC lines

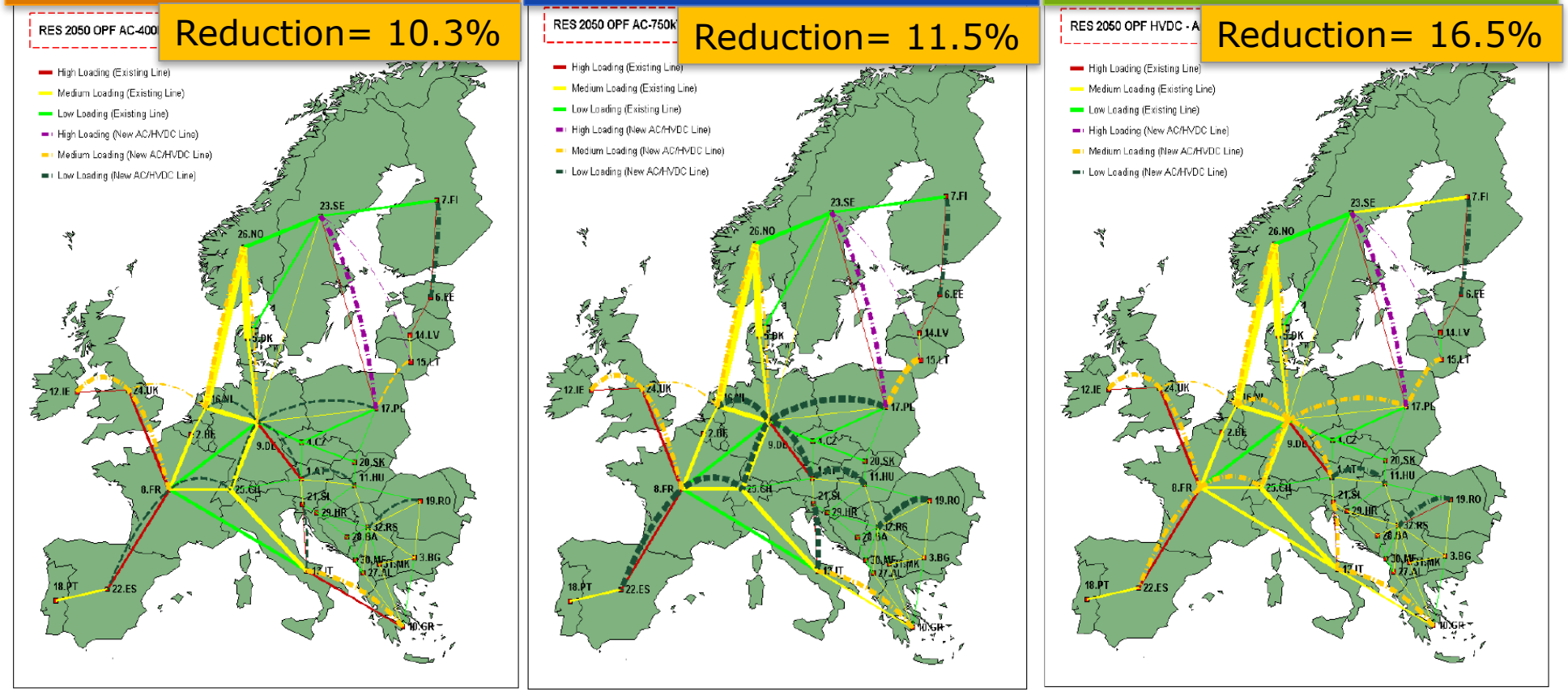


Chatzivasileiadis, Krause, Andersson, Supergrid or local network reinforcements, and the value of controllability - an analytical approach, Powertech 2013

IRENE-40 EU Project

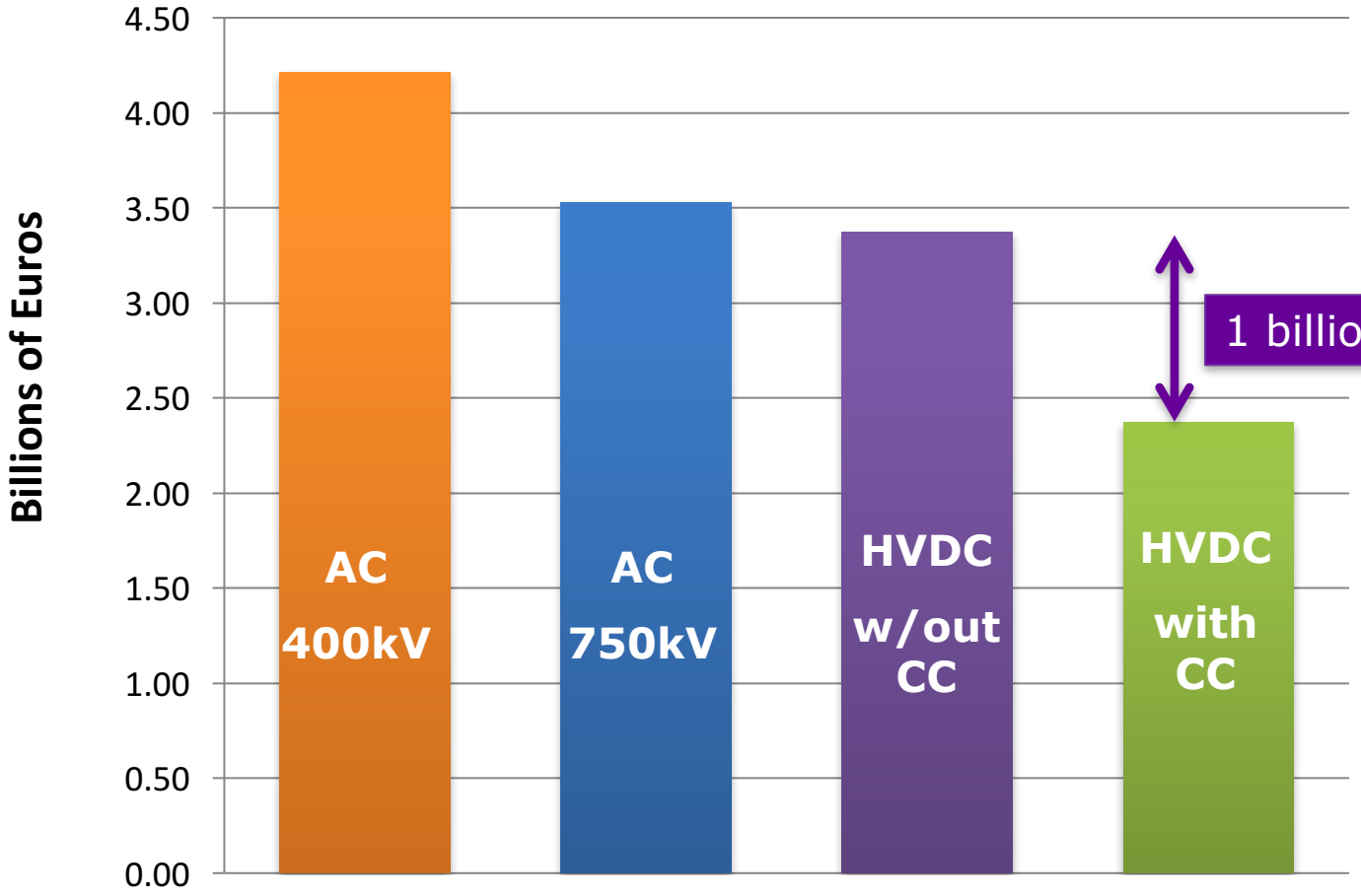
Annual Cost of Operation (RES 2050)

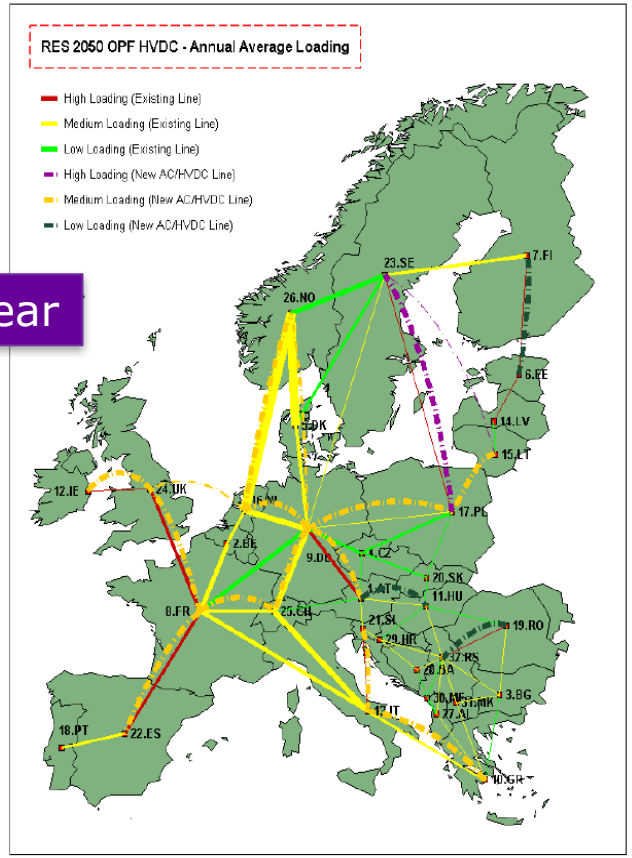
HVAC-400kV	UHVAC-750kV	HVDC
Cost = 95.3 billion Euros	***Cost = 94.0 billion Euros***	***Cost = 88.7 billion Euros***
Reduction= 10.3%	Reduction= 11.5%	Reduction= 16.5%



Minimum Expansion: Cost = ***106.31 billion Euros***

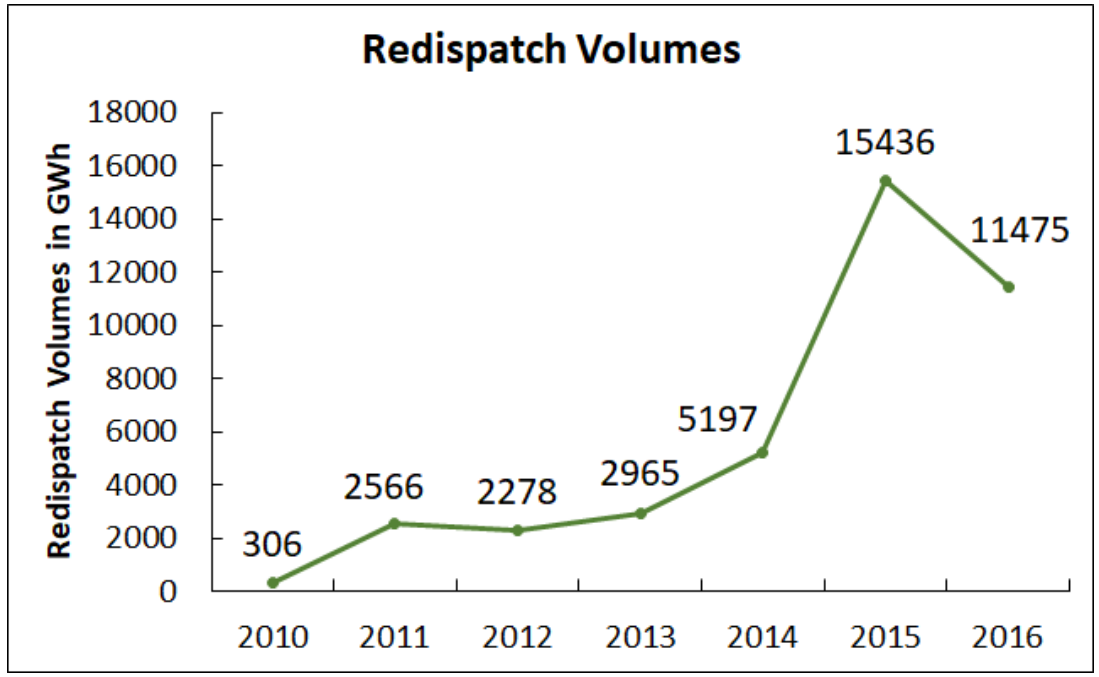
Redispatching costs (RES 2050)

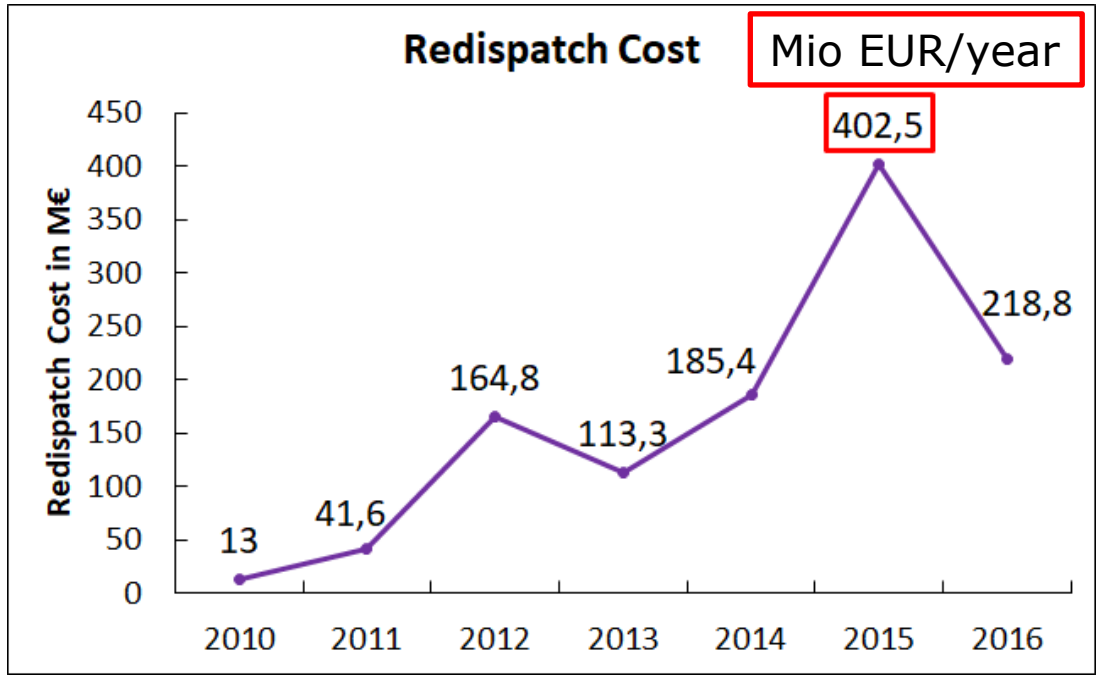




Corrective Control from HVDC lines results in additional savings of 1 billion Euros per year

Redispatching volumes and costs in Germany 2010 - 2016





Source: Bundesnetzagentur

Redispatching is costly and suboptimal!

Can we do better?

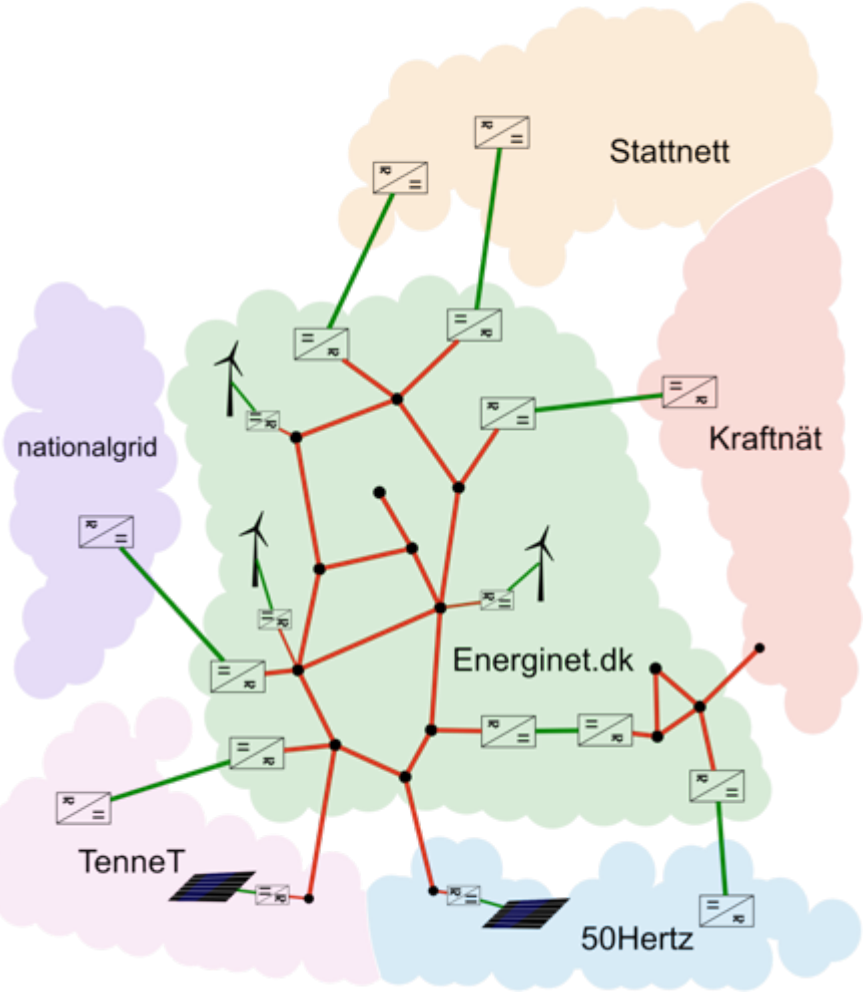
Outline

- Introduction and Motivation
- MULTI-DC: the project
- Challenges:
  - Lack of flexibility → bottlenecks
  - Varying inertia systems
  - Computation and complexity
  - Uncertainty
  - Big data
- MULTI-DC: Research Questions and Value Creation

MULTI-DC

Innovative Methods for Optimal Operation of Multiple HVDC Connections and Grids

- Innovation Fund Denmark Grand Solutions
- Partners:
  - Energinet, Svenska kraftnät
  - DTU, KTH, Univ. of Liege
  - ABB
- 25.7 million DKK
- 4 years; Start 1 May 2017



MULTI-DC

- Significant industry participation
- Investment rate: 56%

- Cofinancing:
  - ENDK: 4.03 million DKK
  - Svk: 4.00 million DKK
  - ABB: 1.40 million DKK

- IFD: 14.4 million DKK

- Advisory Committee:
  - Nordic RSCI (Jens Møller Birkebæk)
  - MOSEK ApS
  - RTE France (Patrick Panciatici)

North Sea Wind Power Hub

Source: Energinet

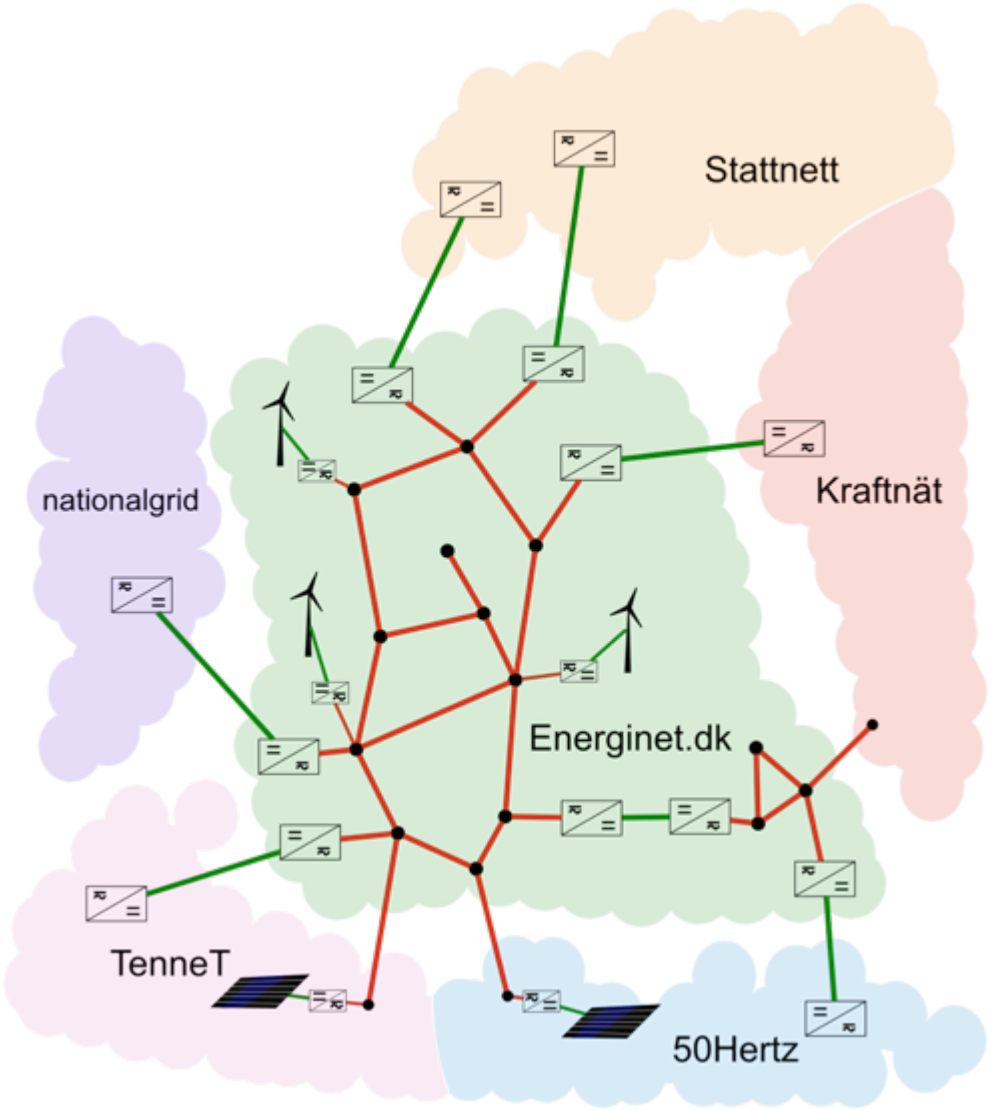
MULTI-DC Objectives

Advanced **control and optimization** methods **for AC and HVDC grids** to:

- Deal with high RES uncertainty & low inertia
- Integrate HVDC controllability
- Capture AC/DC interactions

in order to

- Enhance multi-area system security
- Integrate HVDC in market operation



Three main drivers

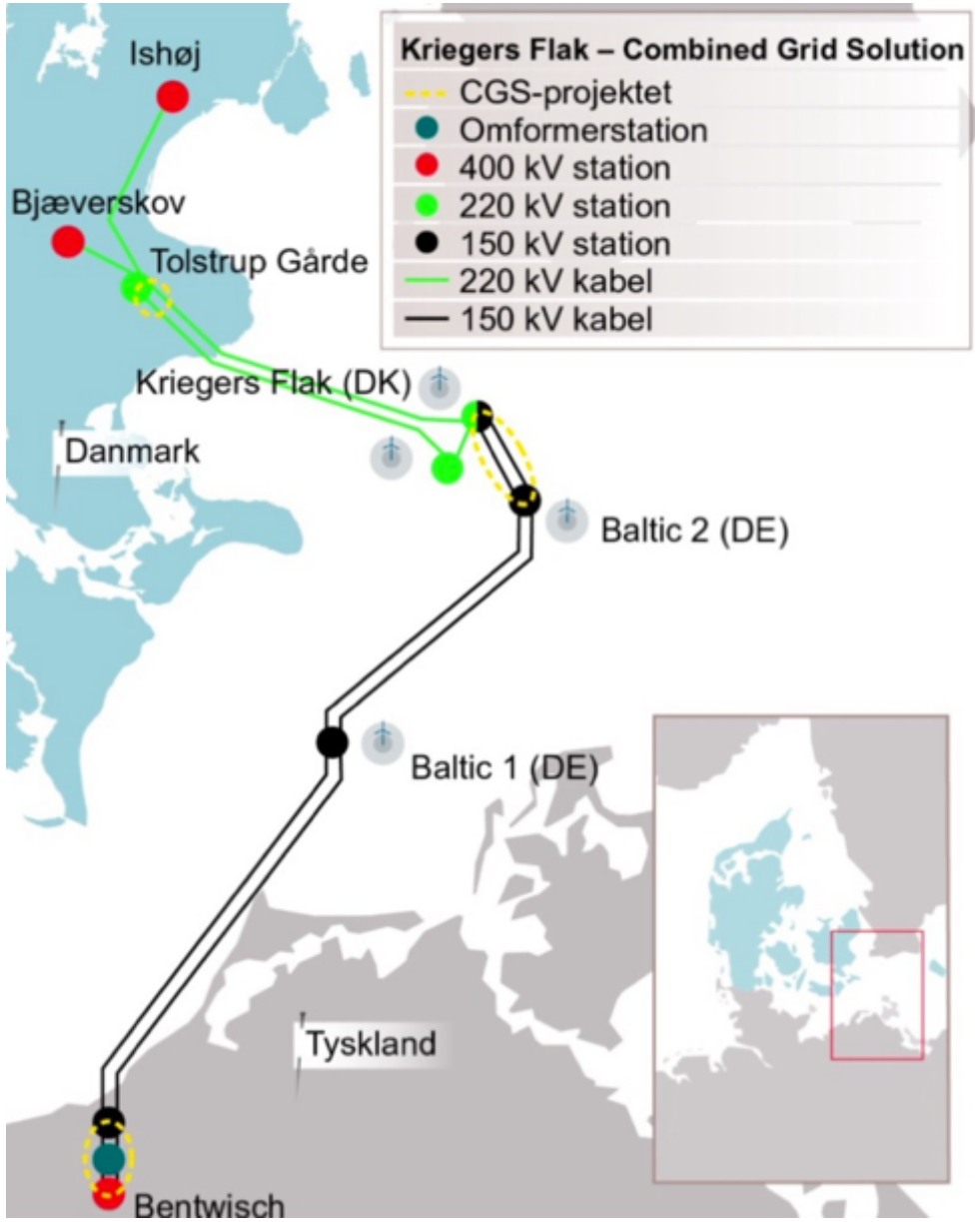
- 100% renewables
  - Varying inertia systems
  - Uncertainty
  - Need for increased flexibility

- 100% inverter-connected devices
  - How is stability and operation affected?
  - How to model them?

- HVDC Grids

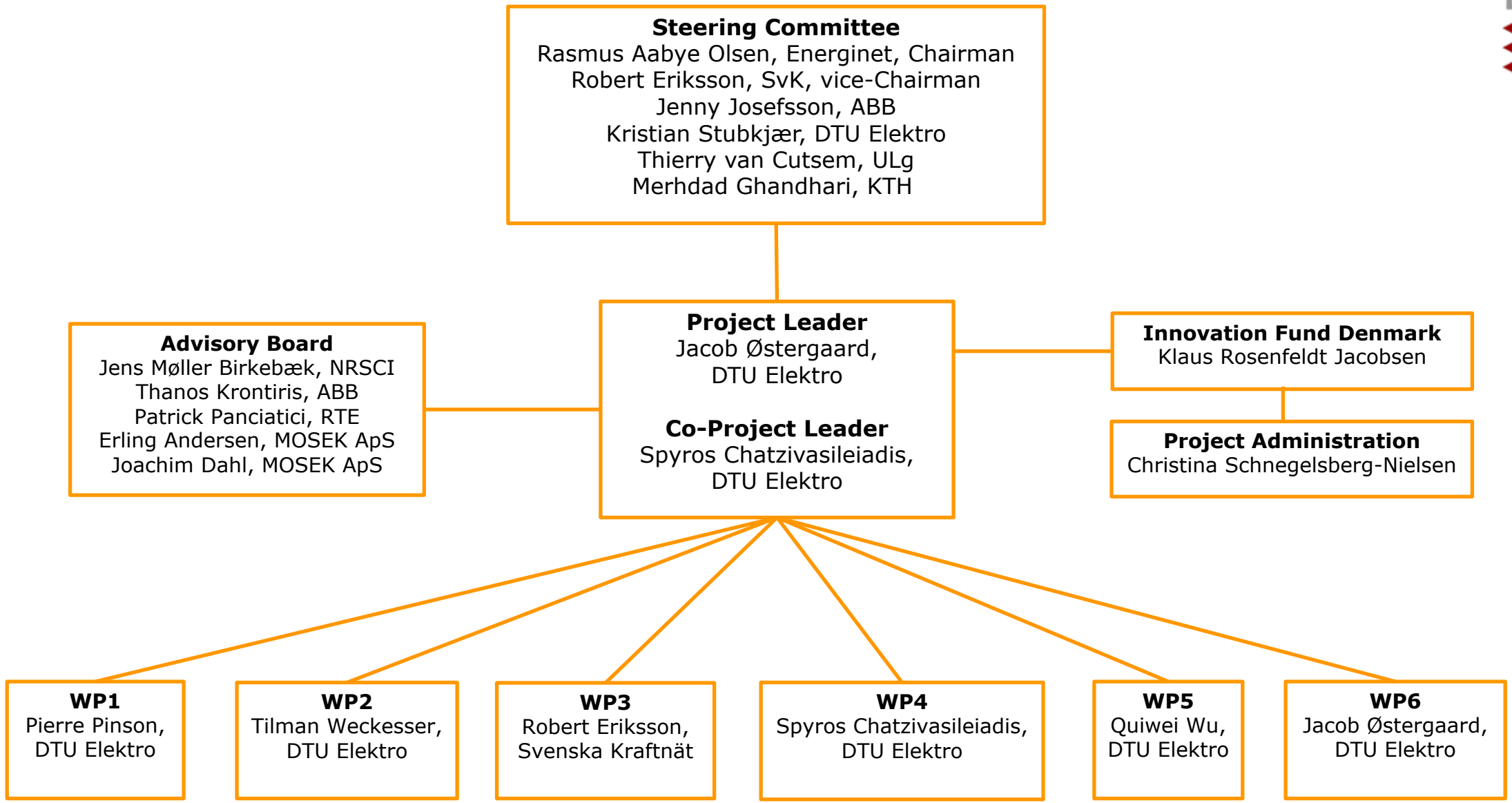
Kriegers Flak

- Denmark – Germany: AC+HVDC
- First interconnection **in the world** that integrates off-shore wind farms along its path
- 400 MW Back-to-Back HVDC
- Wind Farm Kriegers Flak (DK) : 600 MW
- Wind Farm Baltic (DE) : 336 MW
- HVDC Master Controller to:
  - Control voltage
  - Avoid overloadings
  - Ensure market outcome by mitigating wind forecast errors



North Sea Wind Power Hub: "Energy Island"

- Construction of island(s) in the middle of the North Sea
- Integration of up to 100 GW of off-shore wind farms
- HVDC interconnections to Denmark, Germany, the Netherlands, UK, Great Britain, Norway, Belgium
- Coupling the energy markets
- Agreement for pre-feasibility study between Denmark, Germany, and the Netherlands already signed (2017)


Steering Committee
Rasmus Aabye Olsen, Energinet, Chairman
Robert Eriksson, SvK, vice-Chairman
Jenny Josefsson, ABB
Kristian Stubkjær, DTU Elektro
Thierry van Cutsem, ULg
Merhdad Ghandhari, KTH
Advisory Board
Jens Møller Birkebæk, NRSCI
Thanos Krontiris, ABB
Patrick Panciatici, RTE
Erling Andersen, MOSEK ApS
Joachim Dahl, MOSEK ApS
Project Leader
Jacob Østergaard,
DTU Elektro
Co-Project Leader
Spyros Chatzivasileiadis,
DTU Elektro
Innovation Fund Denmark
Klaus Rosenfeldt Jacobsen
Project Administration
Christina Schnegelsberg-Nielsen
WP1
Pierre Pinson,
DTU Elektro
WP2
Tilman Weckesser,
DTU Elektro
WP3
Robert Eriksson,
Svenska Kraftnät
WP4
Spyros Chatzivasileiadis,
DTU Elektro
WP5
Quiwei Wu,
DTU Elektro
WP6
Jacob Østergaard,
DTU Elektro

Outline

- Introduction and Motivation
- MULTI-DC: the project
- Challenges:
  - Lack of flexibility → bottlenecks
  - Varying inertia systems
  - Computation and complexity
  - Uncertainty
  - Big data
- MULTI-DC: Research Questions and Value Creation

AC Transmission bottlenecks do not allow higher exports of Danish wind power

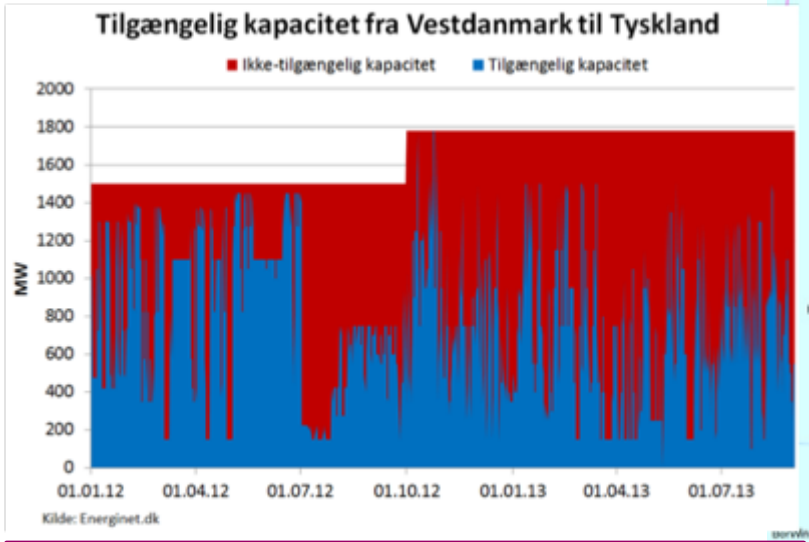
Two corridors between Denmark and Germany

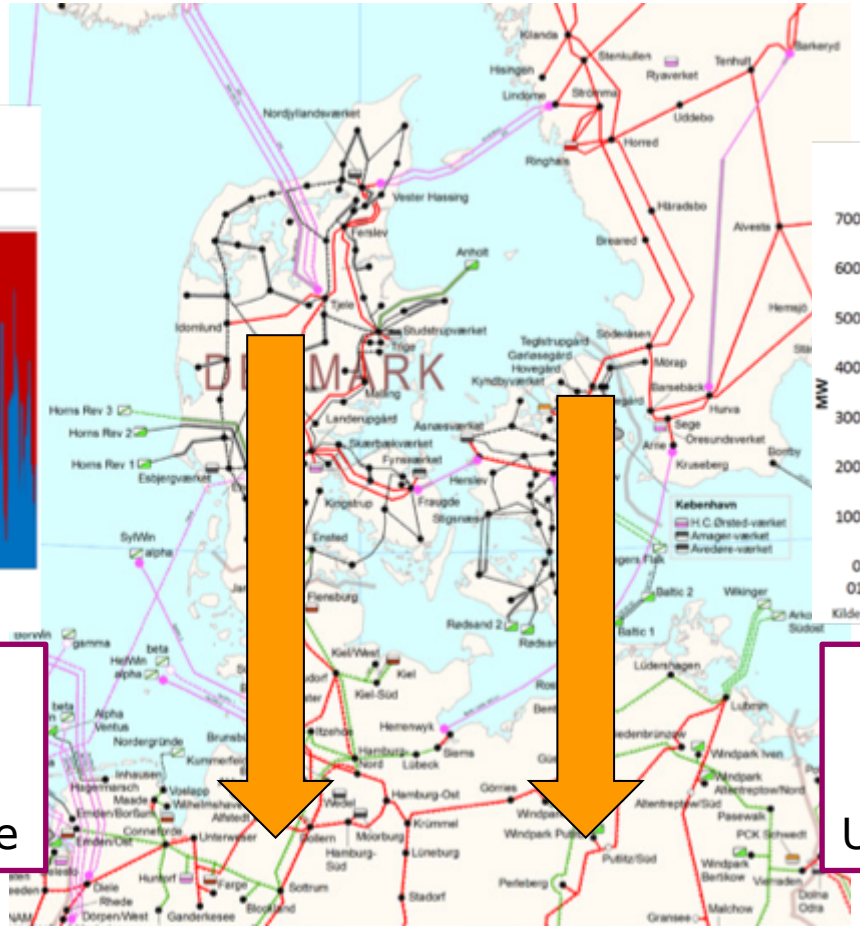
- West corridor: AC lines
- East corridor: DC lines

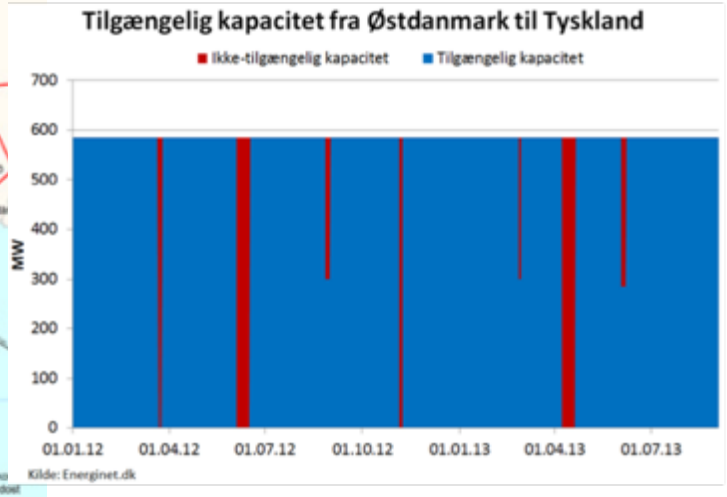
Dansk Energi study on electricity exports:

Data from 2012-2013

AC Transmission bottlenecks do not allow higher exports of Danish wind power







West Denmark → Germany

AC lines

Utilization: **43%-44%** on average

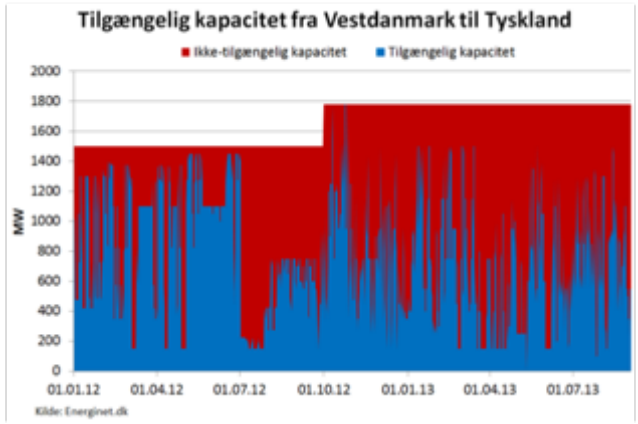
East Denmark → Germany

HVDC lines

Utilization: **~95%** on average

Source: Dansk Energi, "Inblik, Ubrugt kapacitet på elkabel skader dansk eksport", 2014

10% increase in exports → millions in revenues



Per year!

Eksportværdi ved merudnyttelse af eksportbegrænsningen for Vestdanmark-Tyskland kablet

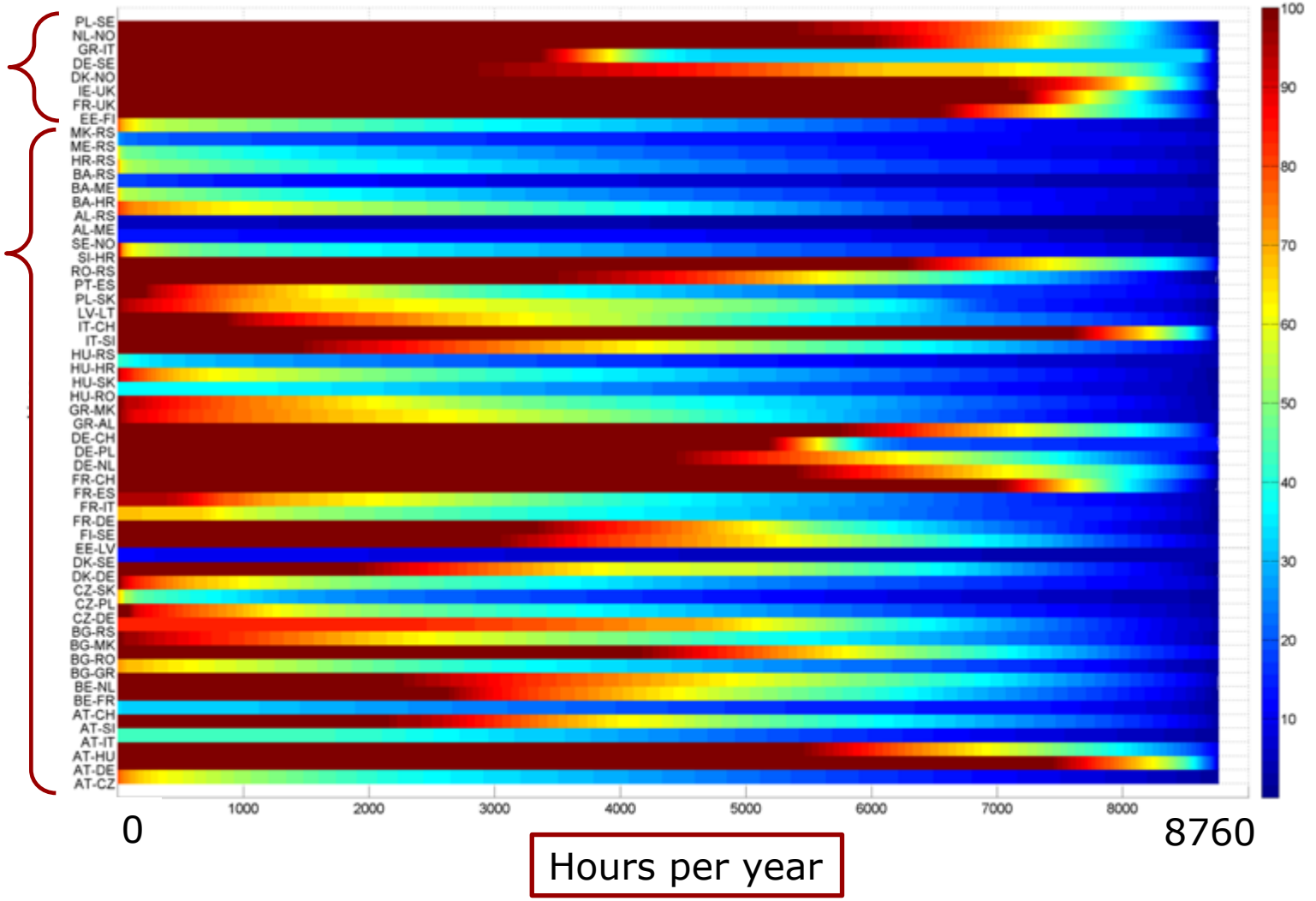
	10% merudnyttelse	50% merudnyttelse
2009	29 mio. kr.	148 mio. kr.
2010	23 mio. kr.	117 mio. kr.
2011	104 mio. kr.	524 mio. kr.
2012	113 mio. kr.	566 mio. kr.

Kilde: Dansk Energis beregninger på baggrund af Energinet.dk tal

Can we achieve 10% extra interconnection capacity though optimal HVDC coordination?

- The underutilization of the AC interconnections betweeen West DK and DE are because of bottlenecks in TenneT's network in Germany
- **Can we bypass or relieve these bottlenecks?**
- HVDC can offer **corrective control** actions, after a contingency occurs → less conservative limits for AC lines
- Optimal coordination of HVDC flows can **reroute the power** through other corridors towards the German network
- **Sharing of reserves** between DK and DE

”Duration Curves”: Tie-line utilization in Europe



100%

50%

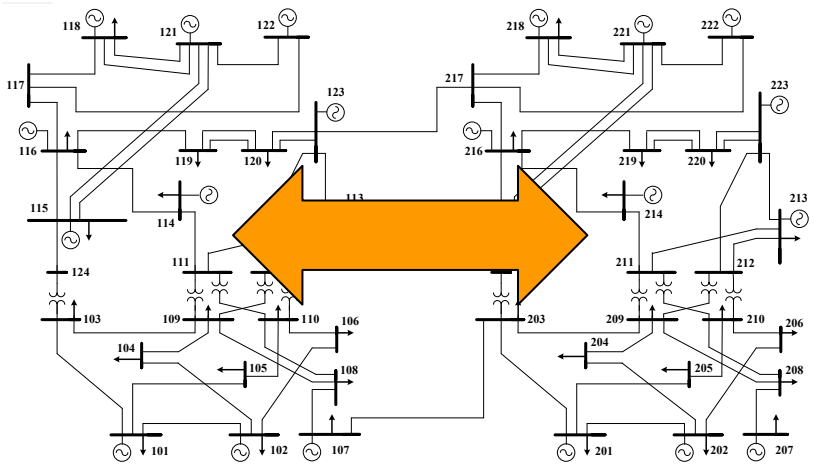
0%

Most AC tie-lines are loaded:

- *less than 50% of their capacity,*
- *for more than 50% of the time*

Sharing of reserves

- Sharing of reserves in multi-area systems
- Higher flexibility → more possible setpoints for tie-line flows
- Improved tie-line utilization
- Higher integration of RES

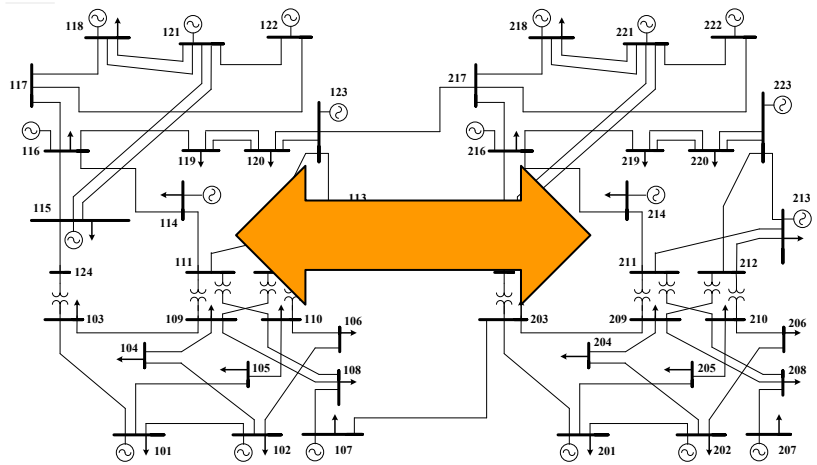


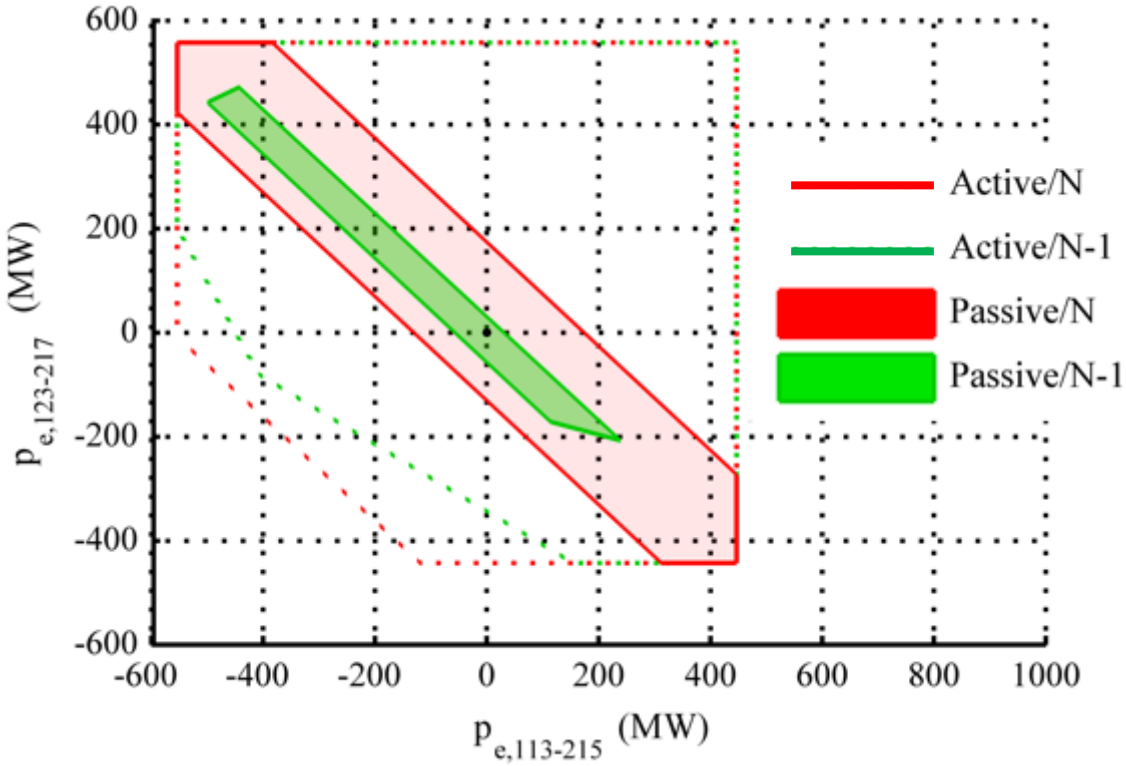
Bucher, Chatzivasileiadis, Andersson, "Managing Flexibility in Multi-Area systems", TPWRS 2015

Halilbasic, Chatzivasileiadis, Pinson, Coordinating Flexibility under Uncertainty in Multi-Area AC and DC Grids, Powertech 2017

Sharing of reserves

- Sharing of reserves in multi-area systems
- Higher flexibility → more possible setpoints for tie-line flows
- Improved tie-line utilization
- Higher integration of RES
- **Sharing of reserves increases flexibility by 240%-600%**
- **Common ancil. serv. products?**



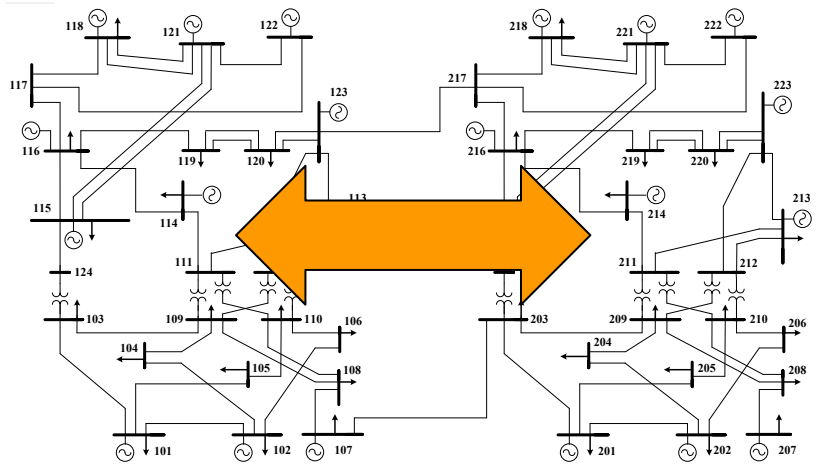


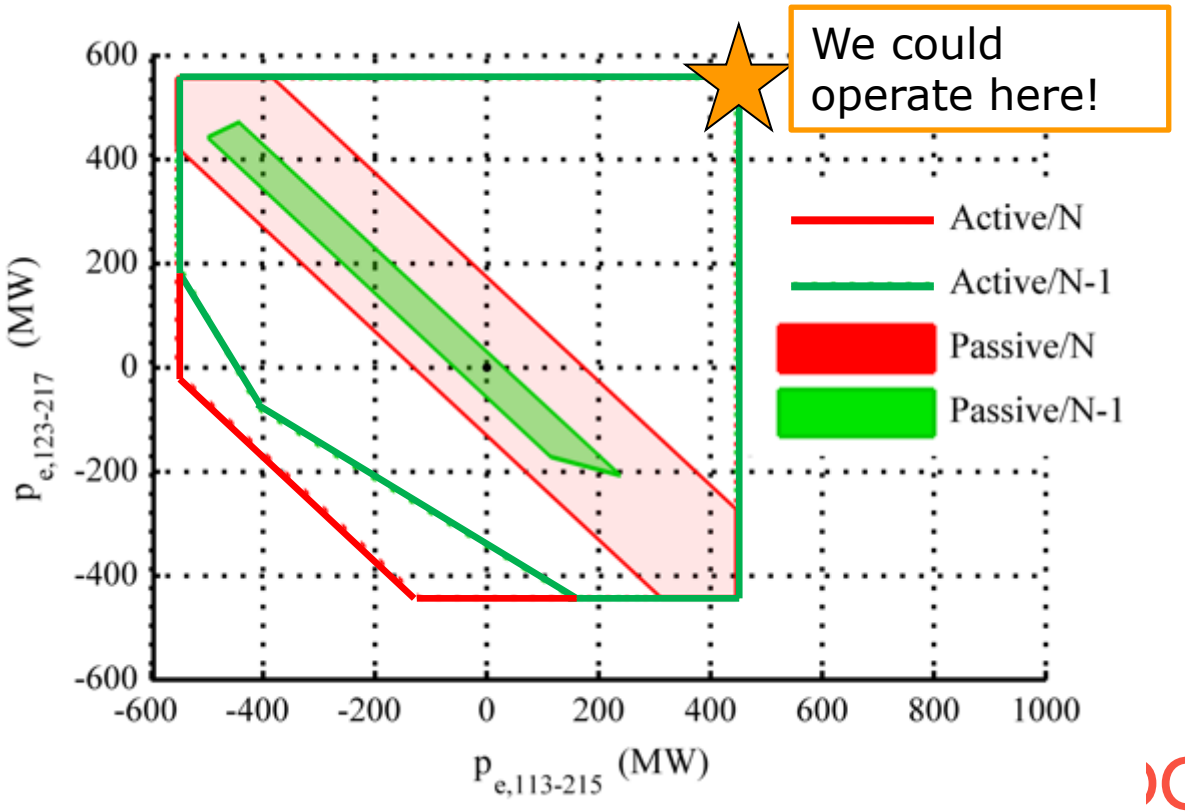
Bucher, Chatzivasileiadis, Andersson, "Managing Flexibility in Multi-Area systems", TPWRS 2015

Halilbasic, Chatzivasileiadis, Pinson, Coordinating Flexibility under Uncertainty in Multi-Area AC and DC Grids, Powertech 2017

Sharing of reserves

- Sharing of reserves in multi-area systems
- Higher flexibility → more possible setpoints for tie-line flows
- Improved tie-line utilization
- Higher integration of RES
- **Sharing of reserves increases flexibility by 240%-600%**
- **Common ancil. serv. products?**



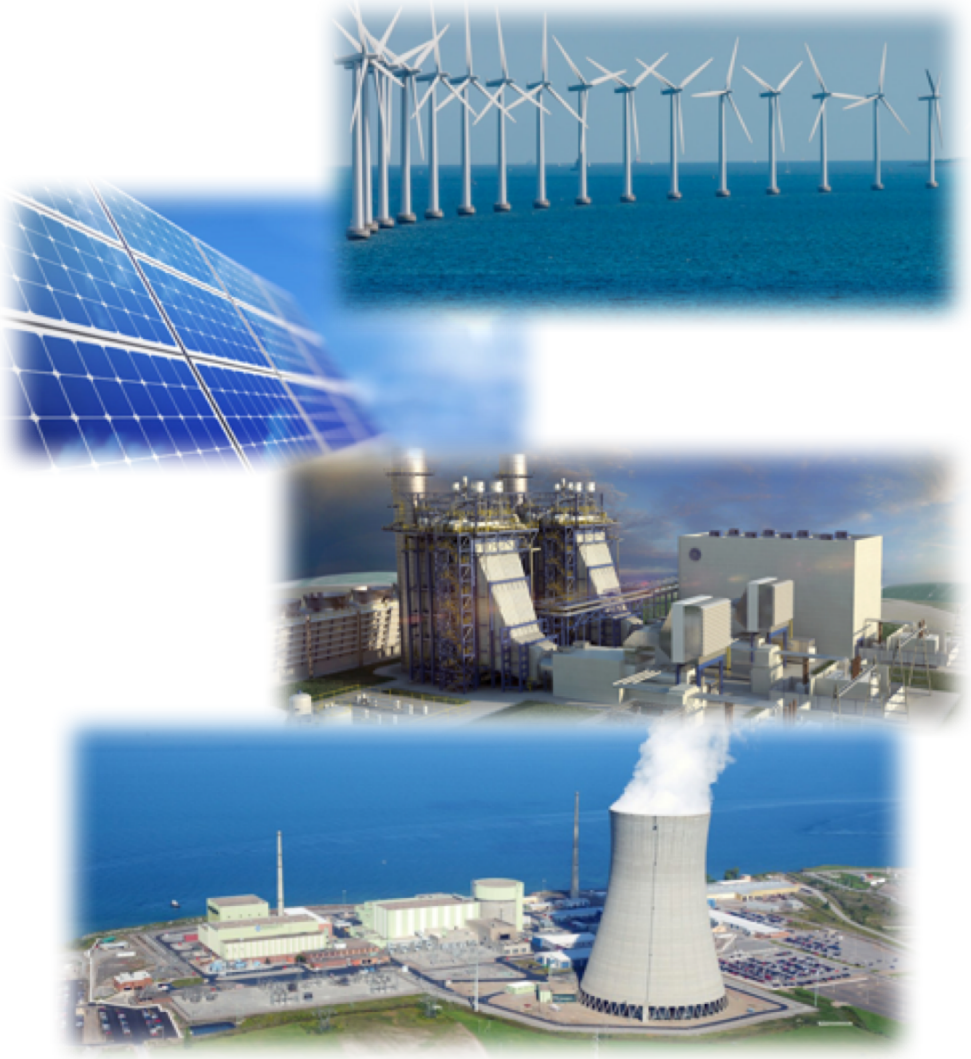


Bucher, Chatzivasileiadis, Andersson, "Managing Flexibility in Multi-Area systems", TPWRS 2015

Halilbasic, Chatzivasileiadis, Pinson, Coordinating Flexibility under Uncertainty in Multi-Area AC and DC Grids, Powertech 2017

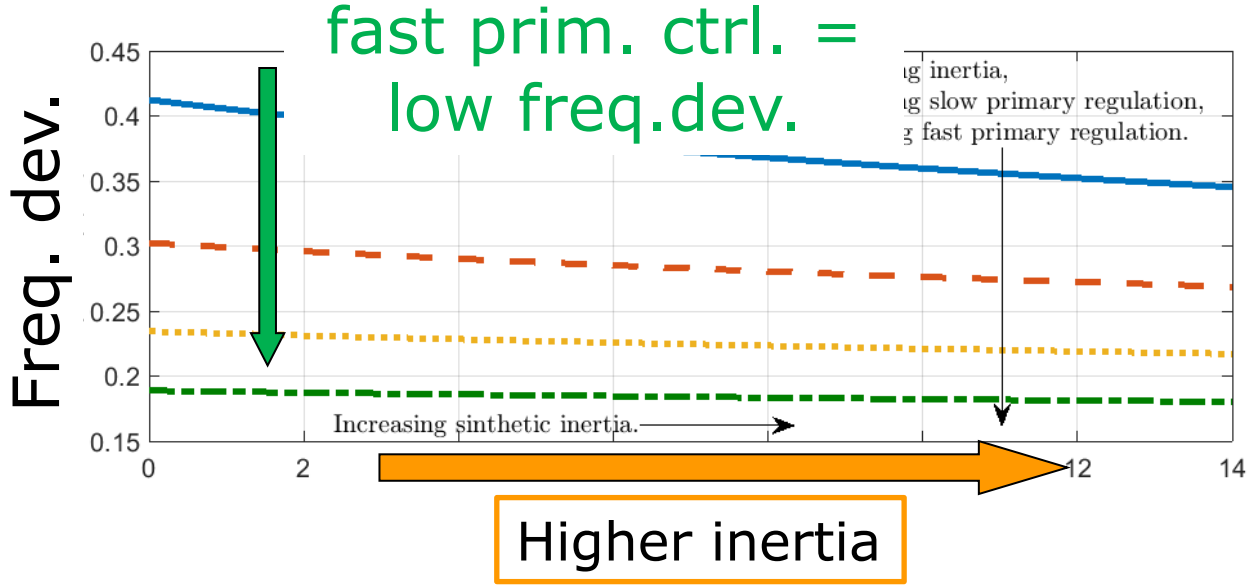
Varying inertia systems

- Due to the varying wind and solar availability, in the future we will have to operate varying inertia systems
- Low inertia: during high wind, no conventional generators would be committed
- High inertia: during low wind, conventional generators have to be dispatched
- Varying inertia: changing from low inertia to high inertia from one hour to the next
- **NEED: robust frequency control → guaranteed performance for uncertain parameters**



Robust control for varying inertia systems

- In general, fast primary frequency control reduces the maximum frequency deviation

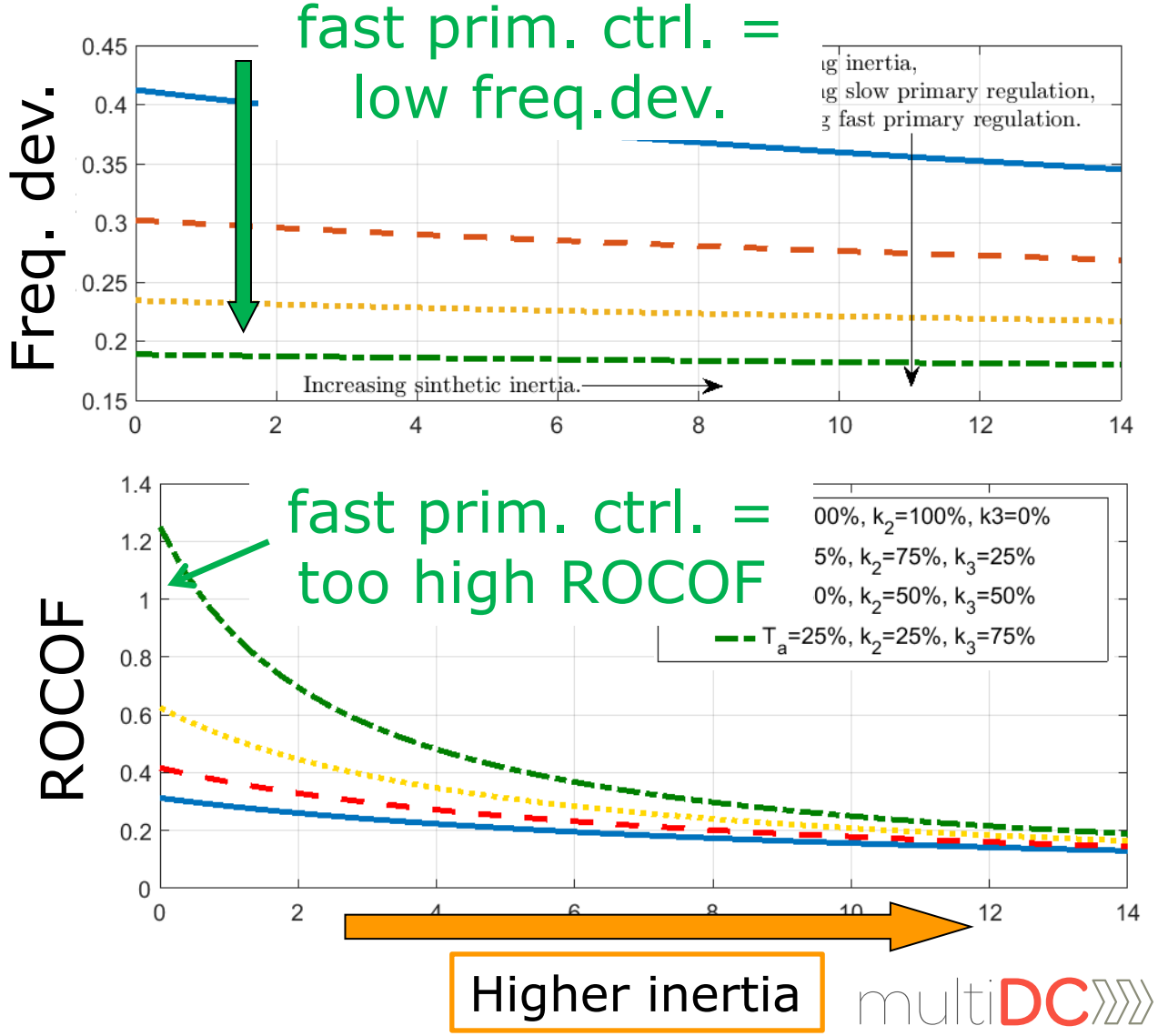


Canevese, Iaria, Rapizza, Impact of Fast Primary Regulation and Synthetic Inertia on Grid Frequency Control, ISGT Europe 2017

Robust control for varying inertia systems

- In general, fast primary frequency control reduces the maximum frequency deviation

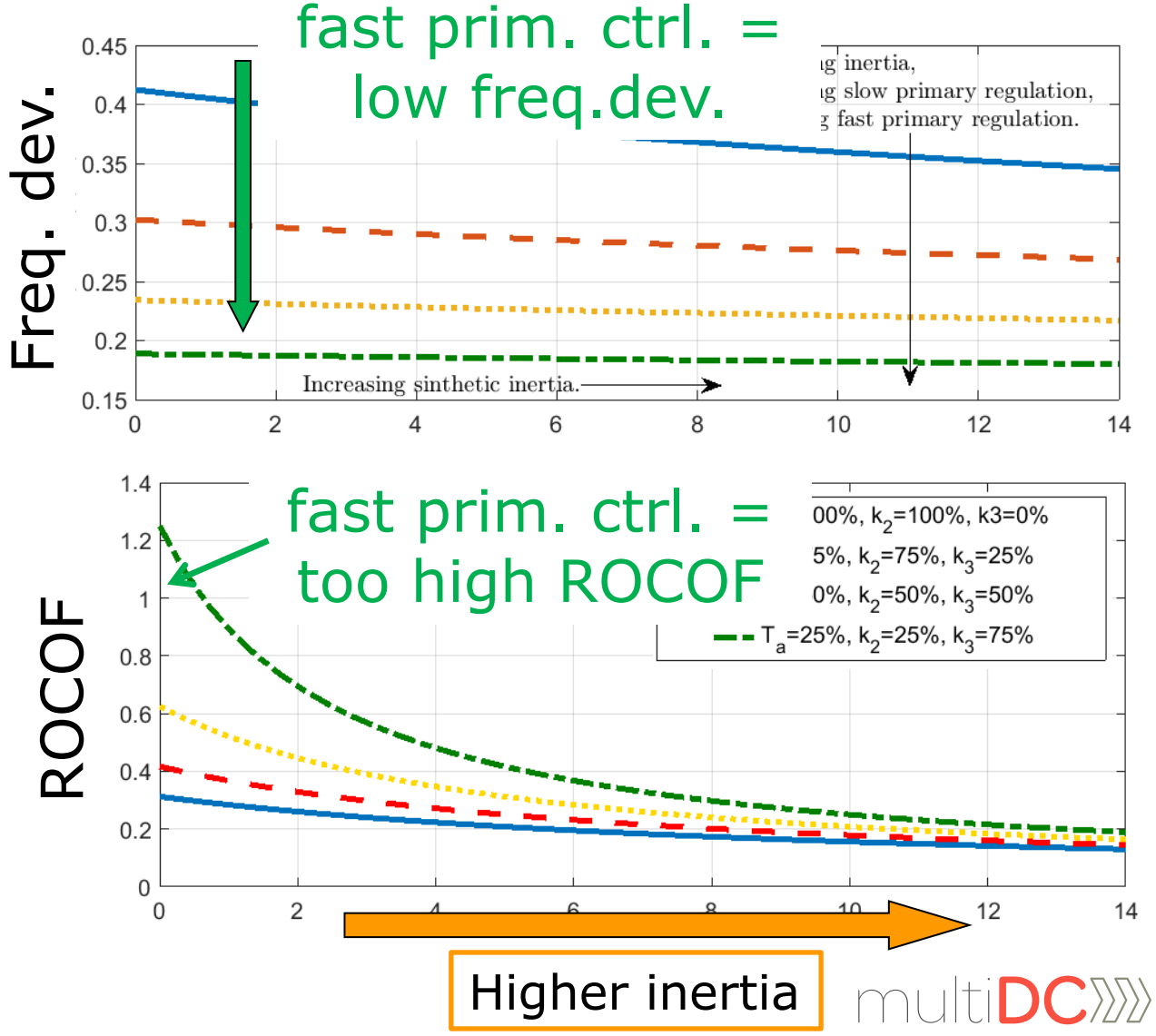
- However, in low inertia systems, fast primary control causes a too fast response, and therefore a too high frequency gradient, i.e. high ROCOF



Canevese, Iaria, Rapizza, Impact of Fast Primary Regulation and Synthetic Inertia on Grid Frequency Control, ISGT Europe 2017

Robust control for varying inertia systems

- In general, fast primary frequency control reduces the maximum frequency deviation
- However, in low inertia systems, fast primary control causes a too fast response, and therefore a too high frequency gradient, i.e. high ROCOF
- *We need to adapt our control parameters for different inertia levels*
- **Or: develop robust control methods**



Canevese, Iaria, Rapizza, Impact of Fast Primary Regulation and Synthetic Inertia on Grid Frequency Control, ISGT Europe 2017

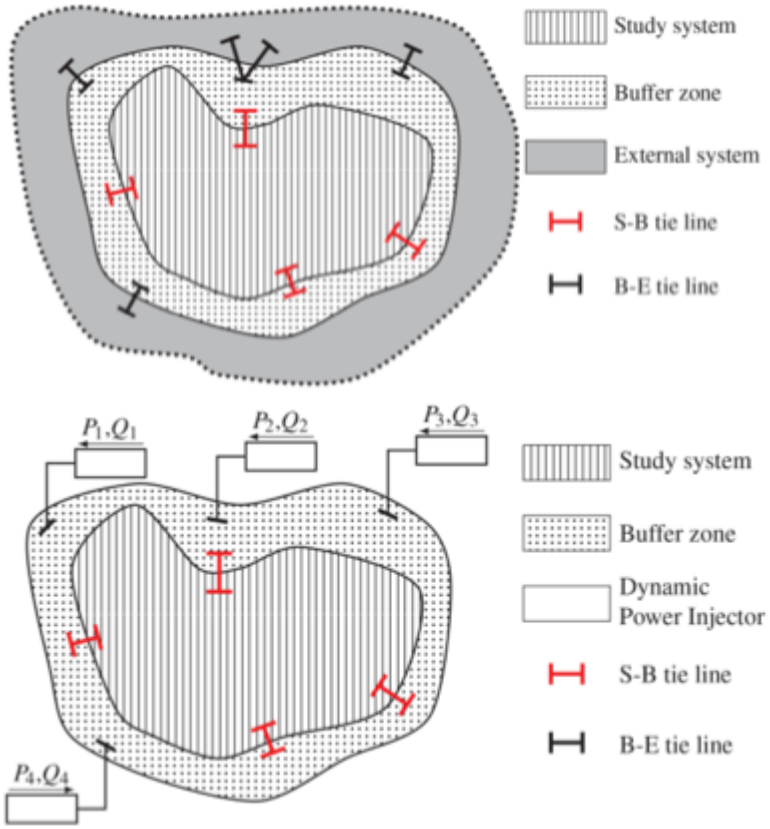
Efficient computations for stability assessment

- Trend: stronger interactions with neighboring systems & **active distribution grids**

- **How do you do consider the dynamic impact of neighboring grids efficiently?**

- New model reduction techniques while preserving accuracy

- **multiDC:**
  - **how do you consider HVDC?**
  - **How do you consider inverter-connected devices in active distribution grids**



T. Weckesser, T. Van Cutsem, "An Equivalent to Represent Inertial and Primary Frequency Control Effects of an External System." IET Generation, Transmission & Distribution.

T. Weckesser, V. Franz, E. Grebe, T. Van Cutsem, "A Model Reduction Approach for Simulation of Long-term Voltage and Frequency Dynamics." 12th IEEE Power and Energy Society PowerTech Conference, Manchester 2017.

Complexity and hidden failures: Risk-based N-k security?

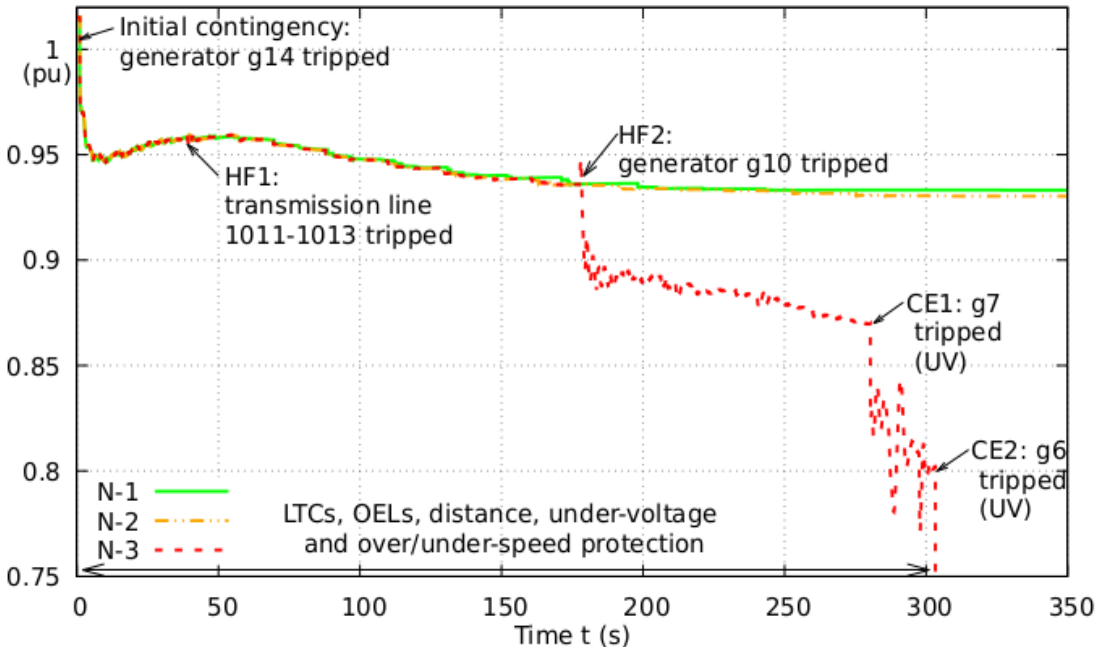
- Thousands of new devices
- Increased controllability
- Increased complexity

- System operated closer to its limits

- Increased probability for critical contingencies

- **Crucial to identify plausible harmful N-k contingencies**

- **multiDC: Risk-based N-k mitigation measures through coordinated HVDC control?**



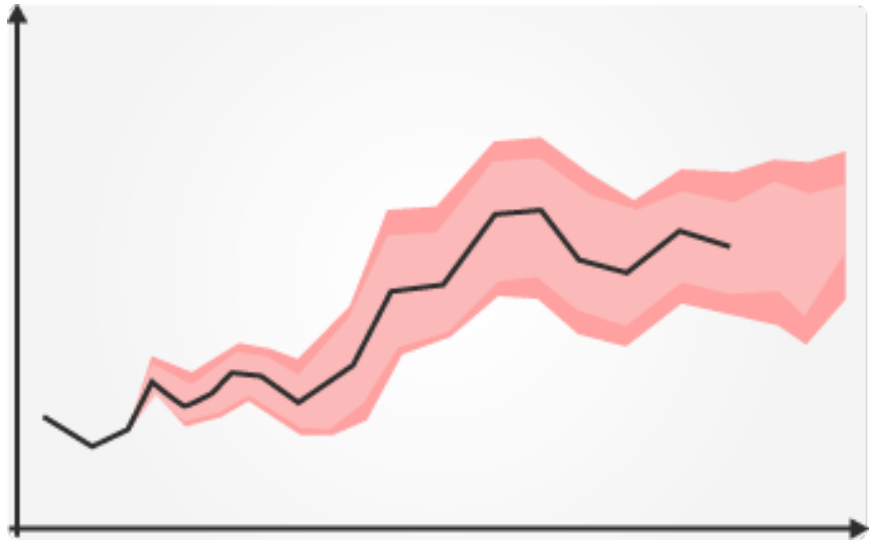
T. Weckesser, T. Van Cutsem, "Identifying Plausible N-k Contingencies: A Practical Approach based on Dynamic Simulations."PSCC 2018 (submitted)

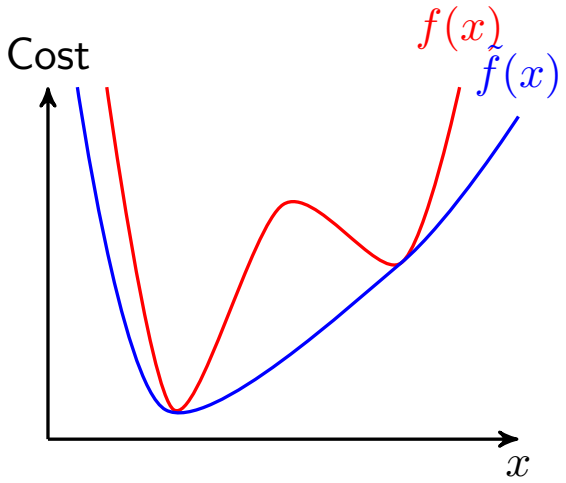
Black-start system restoration

- More than 10 GW of HVDC by 2021 in the Nordic region
- Large amount of inverter-connected generation → difficult to restore the system
- HVDC can act as a firewall and safeguard against massive regional blackouts
- **multiDC: How can we develop black-start restorattion schemes for multiple DC links?**

Dealing with uncertainty

- New methods to **guarantee the global optimum** of non-linear complex problems
  - Under forecast uncertainty
  - Considering N-1 security
  - Using corrective control of generators and HVDC lines



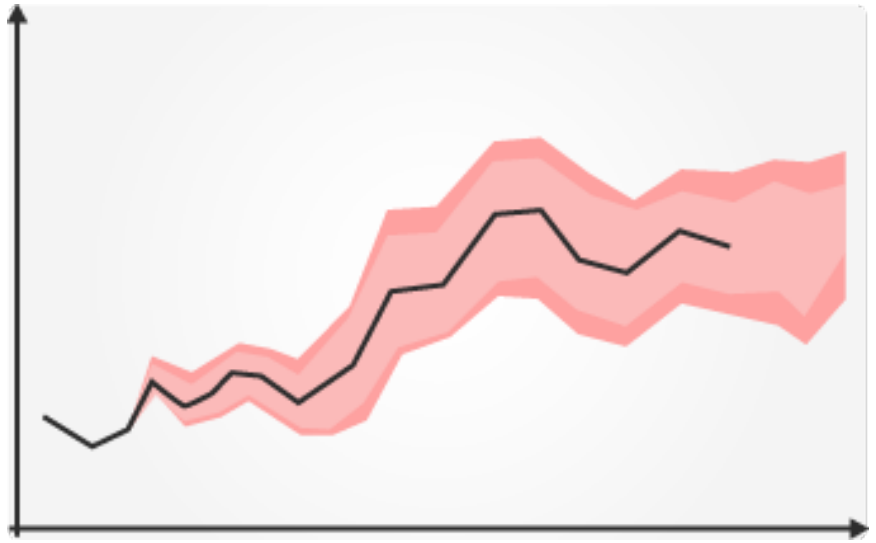


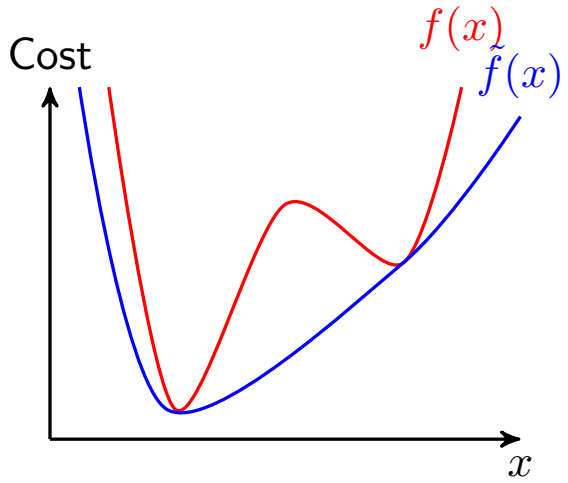
Convex Relaxation

Venzke, Halilbasic, Markovic, Hug, Chatzivasileiadis, Convex Relaxations for Chance-Constrained AC-OPF, TPWRS, 2017

Dealing with uncertainty

- Possible **multiDC contribution**:
  - optimization methods for **Q-V control under uncertainty**
  - finding the **global optimum** to maintain a voltage profile or **minimize losses**





Convex Relaxation

Venzke, Halilbasic, Markovic, Hug, Chatzivasileiadis, Convex Relaxations for Chance-Constrained AC-OPF, TPWRS, 2017

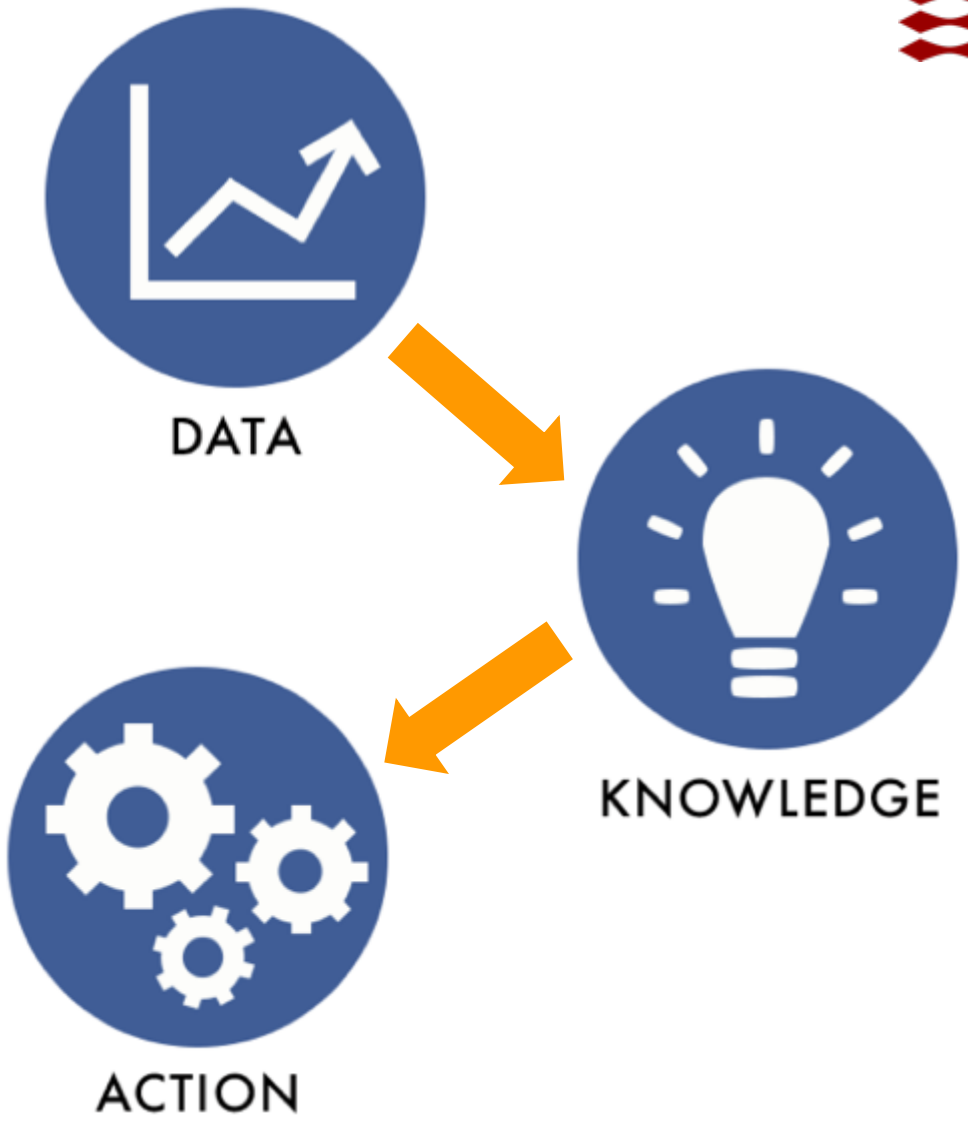
How to handle big data?

- Abundance of measurements from PMUs, SCADA, and other WAMS

- Develop machine learning techniques to efficiently assess the stability of the system

Goals:

- **Predict** instability
- Carry out **corrective control** in time
- Derive an enlarged feasible area for **markets**



Thams, Halilbasic, Pinson, Chatzivasileiadis, Eriksson, "Data-driven Security Constrained OPF", IREP 2017

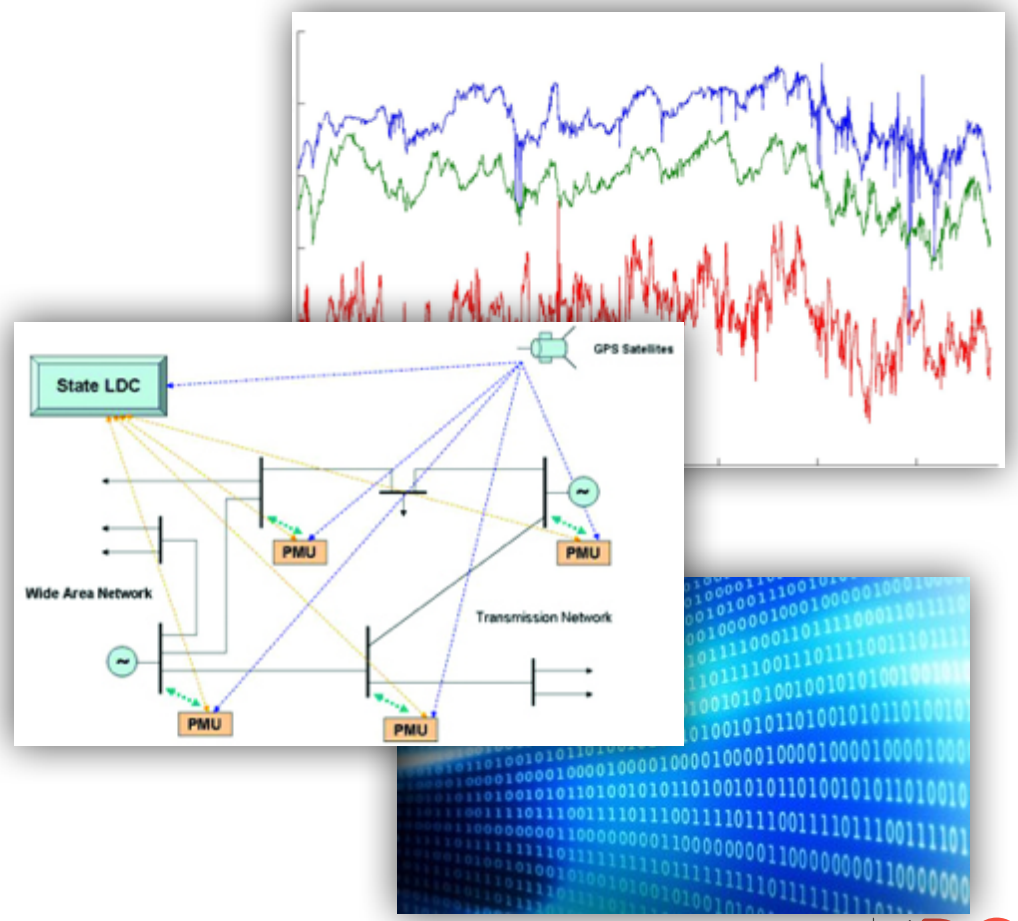
Thams, Hug, Eriksson, Chatzivasileiadis, "Data-driven Dynamic Stability Assessment based on Local Measurements", submitted to PSCC 2018

Data-driven stability assessment based on local measurements

- Abundance of measurements from PMUs, SCADA, and other WAMS

- Development of advanced data-driven methods to *locally* assess the dynamic stability of the system

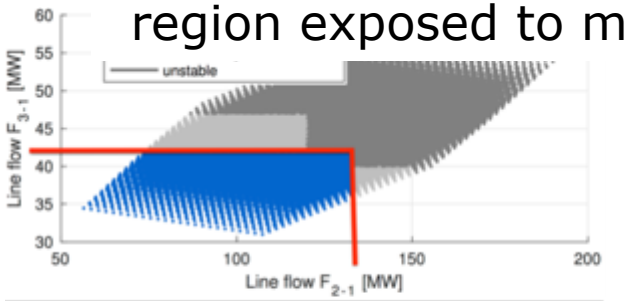
- *Local* control laws for the Multi-terminal VSC-HVDC grid to enhance stability



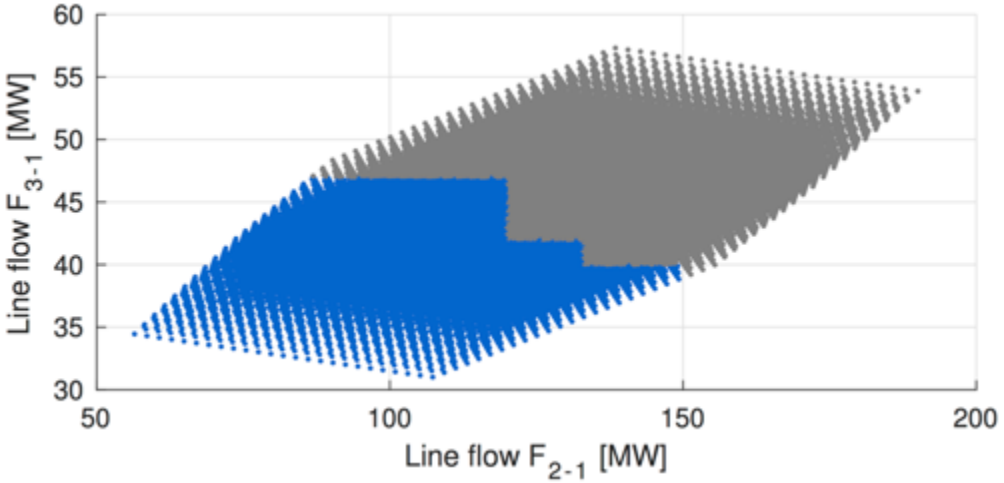
Thams, Hug, Eriksson, Chatzivasileiadis, "Data-driven Dynamic Stability Assessment based on Local Measurements", submitted to PSCC 2018

Data-driven Security-Constrained Optimal Power Flow

Subregion of stability region exposed to market



Data-driven techniques to determine the (non-convex) stability region

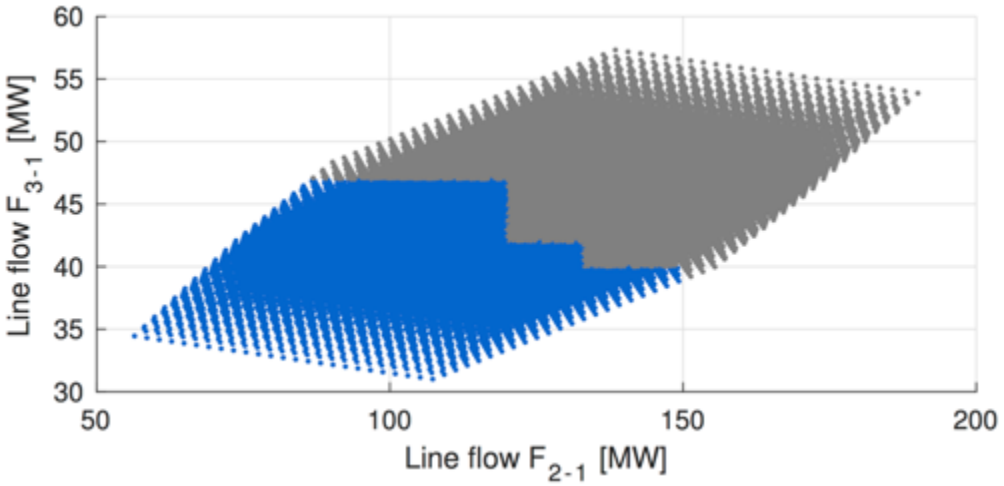


Traditional

Thams, Halilbasic, Pinson, Chatzivasileiadis, Eriksson, "Data-driven Security Constrained OPF", IREP 2017

Data-driven Security-Constrained Optimal Power Flow

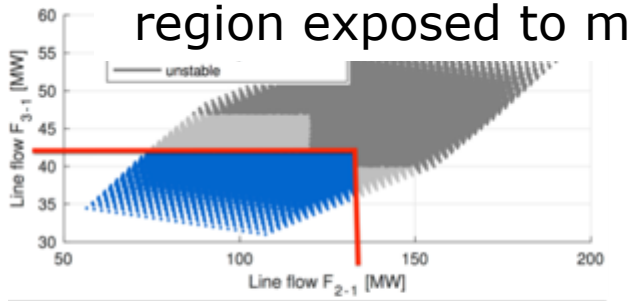
Data-driven techniques to determine the (non-convex) stability region



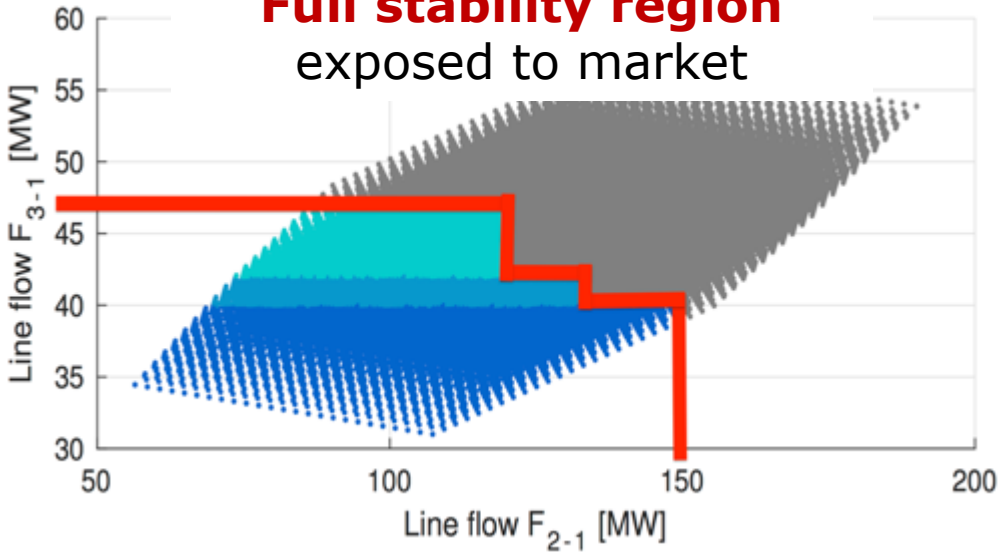
Traditional

Proposed Conditional Line Limits

Subregion of stability region exposed to market



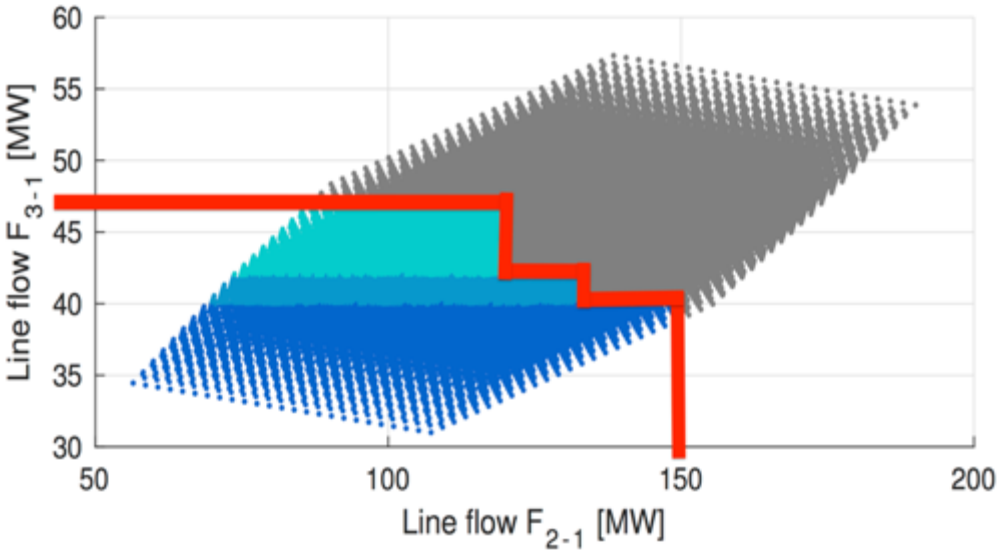
Full stability region exposed to market



Thams, Halilbasic, Pinson, Chatzivasileiadis, Eriksson, "Data-driven Security Constrained OPF", IREP 2017

Data-driven Security-Constrained Optimal Power Flow

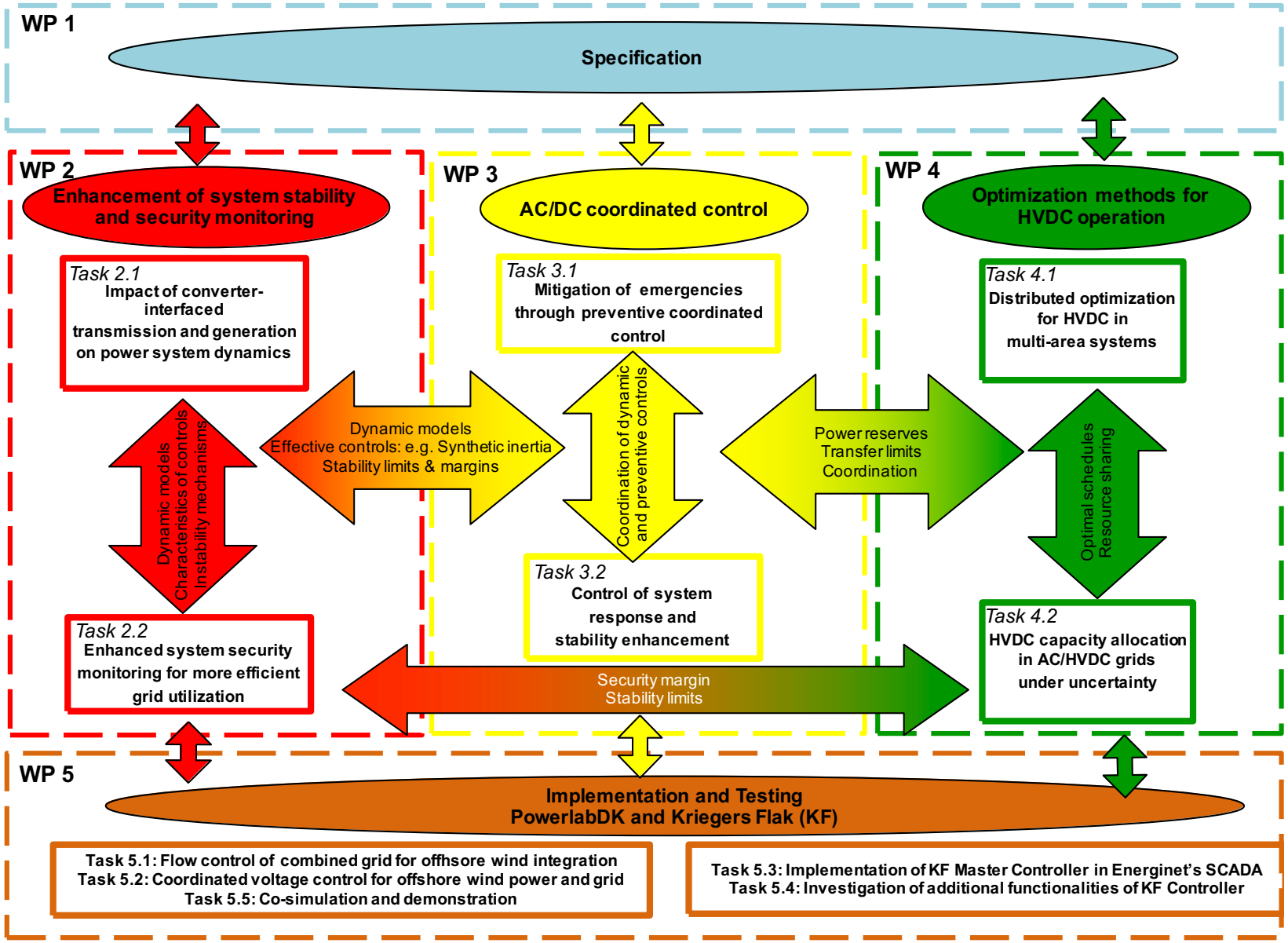
- Develop **efficient machine learning techniques** to determine the non-convex stability region
- Extract conditional rules for line flows
- Allow the **market to determine the most cost-efficient dispatch** considering all security constraints
- **multiDC:**
  - how does the HVDC control change the stability region and the market operation?
  - data-driven HVDC control



Thams, Halilbasic, Pinson, Chatzivasileiadis, Eriksson, "Data-driven Security Constrained OPF", IREP 2017

Outline

- Introduction and Motivation
- MULTI-DC: the project
- Challenges:
  - Lack of flexibility → bottlenecks
  - Varying inertia systems
  - Computation and complexity
  - Uncertainty
  - Big data
- MULTI-DC: Research Questions and Value Creation


WP 1
Specification
WP 2
Enhancement of system stability and security monitoring
WP 3
AC/DC coordinated control
WP 4
Optimization methods for HVDC operation
Task 2.1
Impact of converter-interfaced transmission and generation on power system dynamics
Task 3.1
Mitigation of emergencies through preventive coordinated control
Task 4.1
Distributed optimization for HVDC in multi-area systems
Dynamic models
Characteristics of controls
Instability mechanisms
Dynamic models
Effective controls: e.g. Synthetic inertia
Stability limits & margins
Coordination of dynamic and preventive controls
Power reserves
Transfer limits
Coordination
Optimal schedules
Resource sharing
Task 3.2
Control of system response and stability enhancement
Task 2.2
Enhanced system security monitoring for more efficient grid utilization
Security margin
Stability limits
Task 4.2
HVDC capacity allocation in AC/HVDC grids under uncertainty
WP 5
Implementation and Testing
PowerlabDK and Kriegers Flak (KF)
Task 5.1: Flow control of combined grid for offhsore wind integration
Task 5.2: Coordinated voltage control for offshore wind power and grid
Task 5.5: Co-simulation and demonstration
Task 5.3: Implementation of KF Master Controller in Energinet's SCADA
Task 5.4: Investigation of additional functionalities of KF Controller

Key Milestones (Stop/Go Criteria):

- M1: Set of common test systems, static and dynamic models of power system components, and formulations of the methods to be implemented (November 2018)

- M2: Demonstrate the implemented methods in a simulation environment (May 2020)

- M3: Demonstrate methods in an operationally relevant environment (May 2021)

multiDC Research Questions (selection)

- How do you guarantee an appropriate frequency response for varying inertia systems?
  - Robust control methods

- How to minimize system operator costs under uncertainty?
  - Q-V control and loss minimization under uncertainty
  - Enable HVDC corrective control
  - Minimize redispatcing: Expose remaining security constraints to the market (conditional line limits)
  - Optimization methods guaranteed to find the global minimum (absolute best solution)

- How do you increase the integration and export capability of renewables?
  - Share reserves between areas
  - Take advantage of the HVDC flexibility to reroute power
  - Use HVDC for corrective control

multiDC Research Questions (selection)

- How do you incentivize the provision of inertia and flexibility?
  - Market products for inertia and flexibility?
  - Common ancillary services products in order to share reserves?

- HVDC black start system restoration?

- How will 100% power electronic connected devices affect system response?
  - New types of instability?
  - New computation tools?
  - Need for new grid codes?
  - Can HVDC help?

Innovation and Value Creation

- Currently, the HVDC controls used in the TSO daily operation are too basic

This project

- Advanced coordinated control to enhance stability, increase asset utilization, and market efficiency
- Development of methods relevant to our industrial partners:
  - Energinet, Svenska Kraftnät, ABB, Nordic RSCI

Ultimate Goal

- Creating the options (and evaluate the benefits for Energinet)
- Demonstration of the most promising methods in PowerlabDK
- **Application** of the most relevant methods at **Energinet**

Innovation and Value Creation

Project Strengths

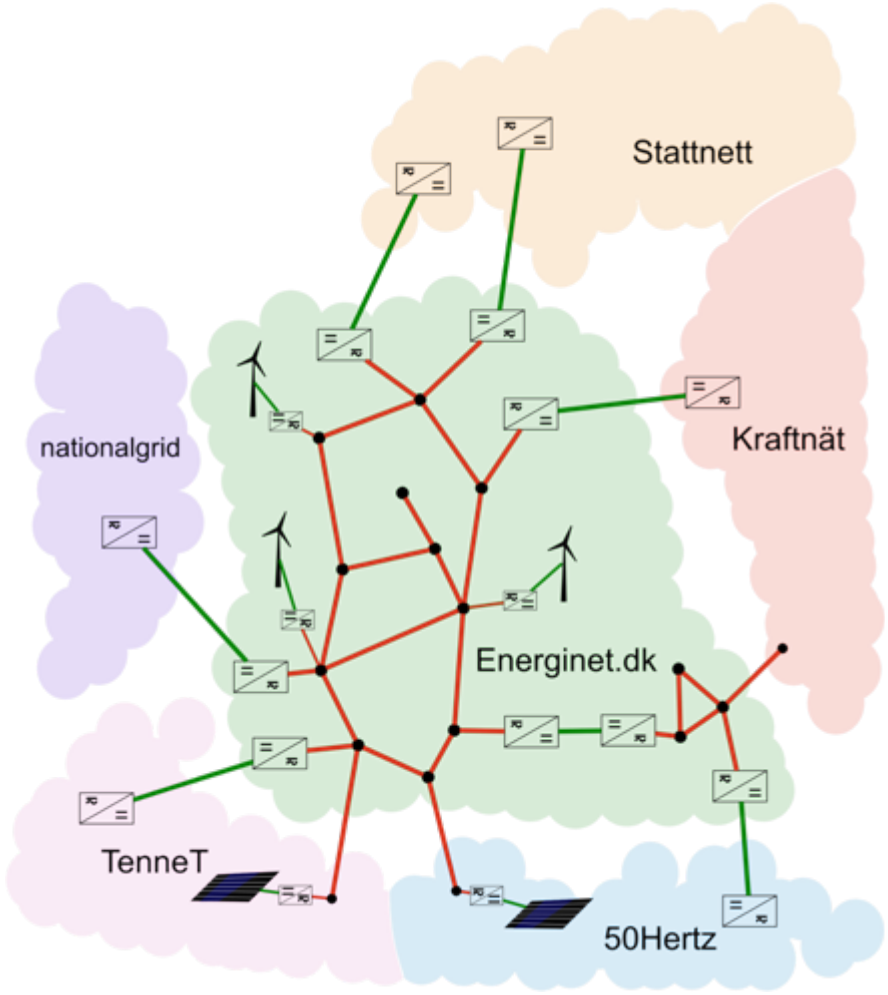
- Involves two neighboring TSOs: Energinet and Svenska kraftnät
  - Study in detail how HVDC controls impact neighboring and multi-area systems
- PowerlabDK → Energinet : (hopefully) straightforward technology transfer
- CAPEX and OPEX savings for the system operators
- Nordic RSCI: build a tool for multi-area HVDC coordination
- Boost export revenues (>100 mio DKK/year)

Conclusions

- Major challenges ahead:
  - Varying inertia systems
  - Increasing uncertainty
  - 100% inverter-connected devices

- Coordinated HVDC control can help:
  - Increase flexibility
  - Enhance stability
  - Minimize operating costs and defer new investments

- Need for:
  - Optimization methods
  - Robust or adaptive control
  - Approaches that tackle uncertainty and big data



Conclusions

- The aim of this project is to develop methods that will solve real problems and will find application in the industry
- Our ultimate goal is to demonstrate our most promising methods in a real operational environment
- Energinet can benefit from methods and practices that:
  - Will make optimal use of the HVDC lines
  - Deal with the low inertia and the uncertainty
- A close collaboration between Energinet and DTU, and the rest of the project partners, can make this project a success

Vi ser frem til et tæt samarbejde!

Tak!

spchatz@elektro.dtu.dk

www.multi-dc.eu (soon online)

Chatzivasileiadis, Ernst, Andersson, The Global Grid, Renewable Energy, 2013