The Energy Analytics & Markets group

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(with ackn. to all funding sources, data providers, collaborators and students, for material and ideas)

Outline

- **Who are we? ... and what we do**

- **Some interesting problems towards an healthy integration of renewables**, e.g.
  - Renewable energy analytics
  - Stochastic market clearing and probabilistic offering
  - Wind providing system services through markets
  - Demand response energy system integration
  - Optimal coordination of HVDC
  - Give us more data!

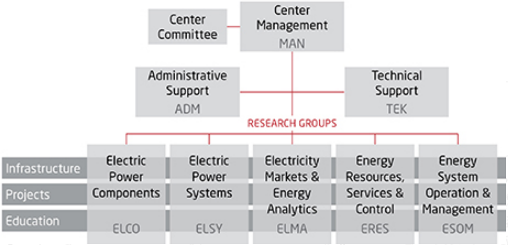
- **Outlook**

... you may find a number of short videos (5-7mins) describing our works on the DTU CEE Youtube Channel

1. **Who are we?... and what we do**

Center for Electric Power and Energy (CEE, at DTU)

- **Established 15 August 2012 as a merger of existing units (Lyngby + Risø)**
  - One of the strongest university centers in Europe with approx. 100 employees
  - A single, clear interface for our external collaboration partners
  - Provides cutting-edge research, education and innovation in the field of electric power and energy to meet the future needs of society regarding a reliable, cost efficient and environmentally friendly energy system
- **Bachelor and Master programs:** Electrical Engineering, Wind Energy, Sustainable Energy
- **Main competences:**
  - Components
  - Power systems
  - Distributed energy resources
  - Market modeling, forecasting and optimization



- **Center agreement (i.e., direct support):** Energinet.dk, Siemens, DONG Energy, Danfoss

Strategic partnerships

- ***Academic partners:***

ETH Zürich (CH)
TU Delft, Delft University of Technology (NL)
(CN)
(DK)
NORDIC FIVE TECH
DTU (DK)
NTNU (NO), Norwegian University of Science and Technology
Aalto University (FI)
Berkeley, University of California (US)
University of Delaware (US)
The Hong Kong Polytechnic University (HK)
Chalmers (SE)
KTH (SE)

+ many more

- ***Commercial and industrial partners:***

Energinet.dk (DK)
DONG energy (DK)
Siemens, Siemens Wind Power (DK)
Elia, Powering a world in progress (BE)
Østkraft, energi til gode oplevelser (DK)
nationalgrid (UK)
IBM (CH)
Vestas (DK)
Pacific Northwest National Laboratory (US)
Danfoss (DK)
seas-nve (DK)
Siemens (DE)
Vestfrost Solutions (DK)
nkt cables (DK)

+ many SME's

- ***Networks:***

Smartgrids (EU)
EERA, European Energy Research Alliance (EU)
iea Energy Technology Network, ISGAN, International smart grid action network (Global)
IEEE PES, Power & Energy Society (Global)

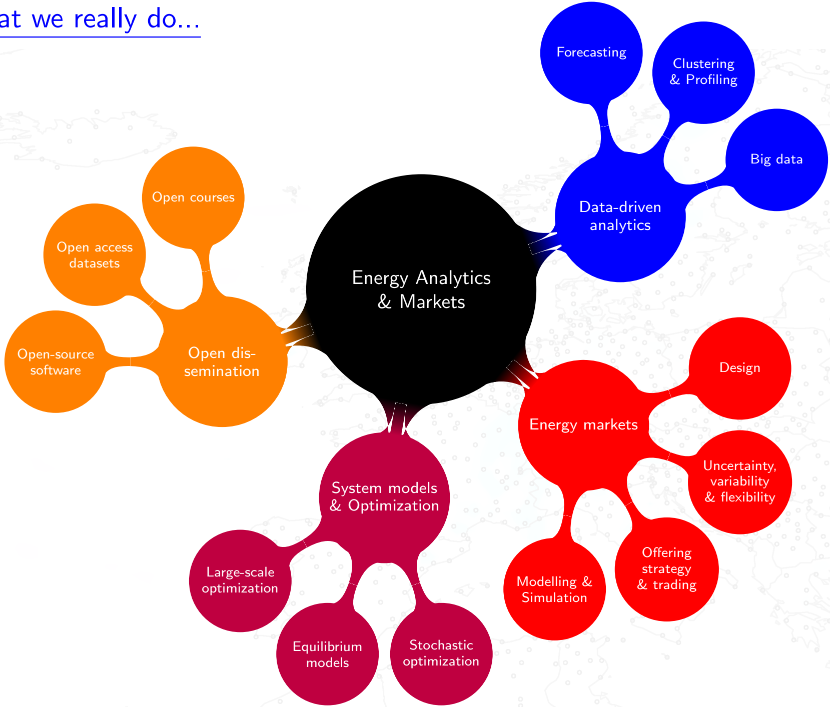
... while building ties with, e.g., EPRI (US), EDF (France), Air Liquide, Danske Commodities, etc.

Who are we? - The Energy Analytics & Markets group

- One of the 5 groups of the Center for Electric Power and Energy, Dpt. of Electrical Engineering

- **Resources:** (10 nationalities)
  - *Faculty:* 1 Prof, 1 Assist. Prof. (+1 more in 2016)
  - *Junior:* 4 post-doc fellows, 9 Ph.D. students (+3 others not at DTU Elektro), 2-3 research assistants
  - + student helpers, and Ph.D. guests from, e.g., China, Brazil, US, Spain, France, Italy, Belgium, etc.
- **Projects** (active in 2015):
  - **EU:** EcoGrid EU, BestPaths
  - **Danish:** 5s, CITIES, EnergyLab Nordhavn
  - **Danish-Chinese:** PROAIN
  - etc.
- **Education:** Various courses on analytics, forecasting, renewables and electricity markets
- (hopefully) recognized leading expertise in energy analytics and markets

What we really do...



Overview paper on forecasting

Statistical Science
2013, Vol. 28, No. 4, 564–585
DOI: 10.1214/13-STS445

Wind Energy: Forecasting Challenges for Its Operational Management

Pierre Pinson

Abstract. Renewable energy sources, especially wind energy, are to play a larger role in providing electricity to industrial and domestic consumers. This is already the case today for a number of European countries, closely followed by the US and high growth countries, for example, Brazil, India and China. There exist a number of technological, environmental and political challenges linked to supplementing existing electricity generation capacities with wind energy. Here, mathematicians and statisticians could make a substantial contribution at the interface of meteorology and decision-making, in connection with the generation of forecasts tailored to the various operational decision problems involved. Indeed, while wind energy may be seen as an environmentally friendly source of energy, full benefits from its usage can only be obtained if one is able to accommodate its variability and limited predictability. Based on a short presentation of its physical basics, the importance of considering wind power generation as a stochastic process is motivated. After describing representative operational decision-making problems for both market participants and system operators, it is underlined that forecasts should be issued in a probabilistic framework. Even though, eventually, the forecaster may only communicate single-valued predictions. The existing approaches to wind power forecasting are subsequently described, with focus on single-valued predictions, predictive marginal densities and space–time trajectories. Upcoming challenges related to generating improved and new types of forecasts, as well as their verification and value to forecast users, are finally discussed.

Key words and phrases: Decision-making, electricity markets, forecast verification, Gaussian copula, linear and nonlinear regression, quantile regression, power systems operations, parametric and nonparametric predictive densities, renewable energy, space–time trajectories, stochastic optimization.

1. INTRODUCTION

Increased concerns related to climate evolution and energetic independence have supported the necessary technological and regulatory developments to broaden the energy mix all around the world, with a particular emphasis placed on renewable energy sources (Letcher, 2008). Among the various candidates, wind energy showed the most rapid and consistent deployment of power generating capacities. By June 2012, the cumulative installed wind power capacity worldwide had reached 254 GW, and it is still increasing at a rapid pace [WWEA (World Wind Energy Association), 2012]. Besides all the mathematical and statistical challenges in the development of turbines (aerodynamics, materials and structures, etc.), and in the deployment of wind energy capacities (e.g., wind resource estimation, logistics optimization), those relating to power systems operations and electricity markets have attracted substantial and growing interest over the last 3 decades. This is since, in contrast with conven-

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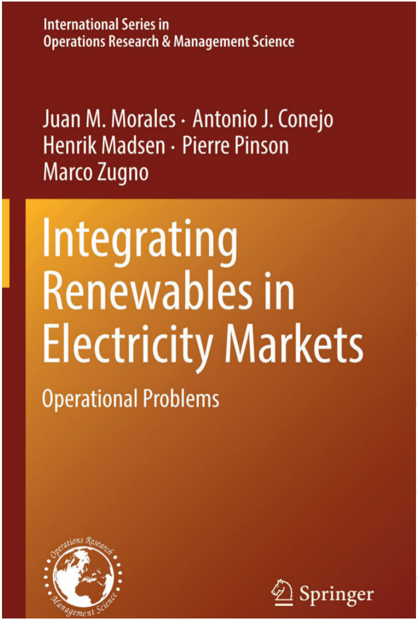
564

Statistical Science
Special issue on "Mathematics of Planet Earth"

Published in Dec. 2013
(**open access!**)

Book on renewables in electricity markets



Available from Dec. 2013
(**sorry, not open access!**)

Topics:

- Renewable energy modeling and forecasting
- Day-ahead market-clearing with significant share of renewables
- Balancing markets
- Managing uncertainty (rewarding flexibility)
- Impact of renewables on market quantities
- Trading stochastic power generation
- Virtual power plants (meaningful association and operation)
- Demand-side aspects

2. **Some interesting problems towards an healthy integration of renewables**

Renewable energy analytics as a breakthrough

- The **MIT Technology Review**:
  - founded at MIT in 1899
  - daily review/analysis of technological innovation worldwide
  - *impact*: 580.000 members and 2.400.000 website visitors per month!

MIT Technology Review

NEWS & ANALYSIS FEATURES VIEWS MULTIMEDIA DISCUSSIONS TOPICS POPULAR: FANCY ROBO-FOOTWORK

Digital Summit
June 9-10, 2014
San Francisco
REGISTER NOW

Turbines at this wind farm north of Limon, Colorado, collect and transmit massive amounts of data.

Smart Wind and Solar Power

Big data and artificial intelligence are producing ultra-accurate forecasts that will make it feasible to integrate much more renewable energy into the grid.

Breakthrough
Ultra-accurate forecasting of wind and solar power.

Why It Matters
Dealing with the intermittency of renewable energy will be crucial for its expansion.

Key Players
+ Xcel Energy
+ GE Power
+ National Center for Atmospheric Research

Wind power is booming on the open plains of eastern Colorado. Travel seven miles north of the town of Limon on Highway 71 and then head

10 Breakthrough Technologies 2014

- The **10 breakthrough technologies 2014**:
  - genome editing
  - microscale 3D printing
  - neuromorphic chips
  - brain mapping
  - etc.

  - **renewable energy analytics**, especially *short-term forecasting* (0-72h) and its *dynamic uncertainty*

[See link:
MIT Technology Review - Smart Wind and Solar Power]

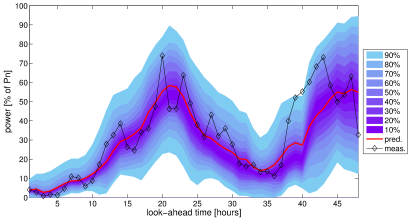
Analytics in a probabilistic framework

- **Modelling**, **forecasting**, and **decision-making** ought to be done in a probabilistic framework

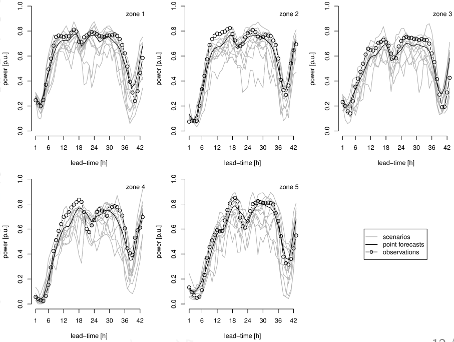
- We are recognized for **leading contributions in that field**, e.g.,

  1. *Innovative probabilistic forecasting products*
  2. Reference frameworks to *benchmark and evaluate forecasts*
  3. Most cited work on *wind energy in electricity markets*
  4. First *weather radar offshore* for analytics at large offshore wind farms

Density forecasts: (*ex:* wind farm in Denmark)



Space-time scenarios: (*ex:* 5 areas in Denmark)



Revisiting market-clearing procedures

- Day-ahead market-clearing insures an **optimal match of production and demand**, a fair amount of time prior to operations, **regardless of the ‘nature’ of offers/bids**
- With increased variability and uncertainty to be dealt with, the system should be placed in a state permitting to optimally cope with **whatever could realistically happen**
- The alternative schools of thoughts:
  - *Conventional sequential market-clearing(s)*, where day-ahead aspects and balancing are decoupled
  - *Stochastic optimization*, accounting for expected costs of balancing
- The more practical, and still efficient, solutions:
  - *Conventional market-clearing with improved dispatch of stochastic production*
  - *Robust optimization based dispatch*
- These are current research problems...

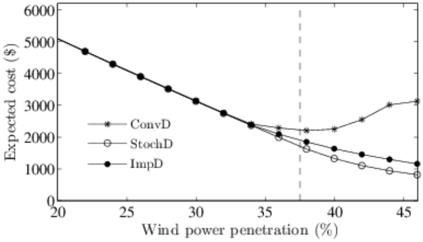
Illustration: costs of power system operation

- **Representative 24-bus system** (IEEE RTS, Grigg *et al.* (1999)), with total demand of 2GW and various types of generators (2 wind farms, for simplicity)

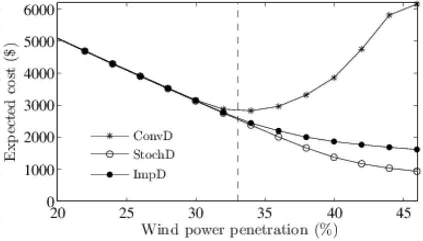
- Realistic unit characteristics (also, Bouffard *et al.* (2005)) and load, while varying wind power penetration and spatial correlation

- Energy-only **Market-clearing:** *conventional*, *stochastic optimization*, *conventional with improved dispatch of stochastic power generation*

- Costs of power system operation highly impacted by market-clearing approach



$\rho = 0.35$



$\rho = 0.75$

Morales JM, Zugno M, Pineda S, Pinson P (2014). Electricity market clearing with improved scheduling of stochastic production. *Eup. J. Op. Res.*

Dispatch under uncertainty

probabilistic offers

evaluation of offers

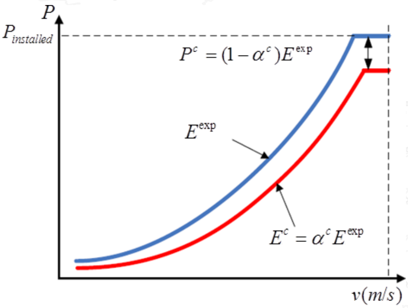
coupled day-ahead and real-time markets

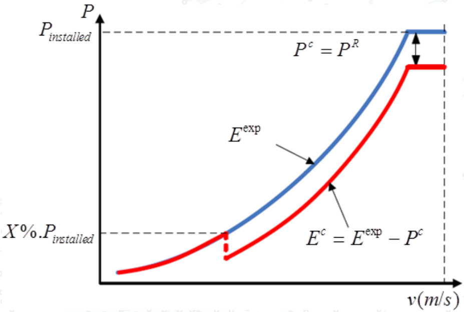
- **The narrative fallacy:** Do we really believe we can offer renewables deterministically with lead times of 12-36 hours ahead?
- Why not adapting market designs to reveal and accommodate the true cost of renewables' uncertainty?

Papakonstantinou A, Pinson P (2015). Information uncertainty in electricity markets: Introducing probabilistic offers. *under review*

Wind power offering system services

- In a market environment, wind power producers may offer services under alternative strategies

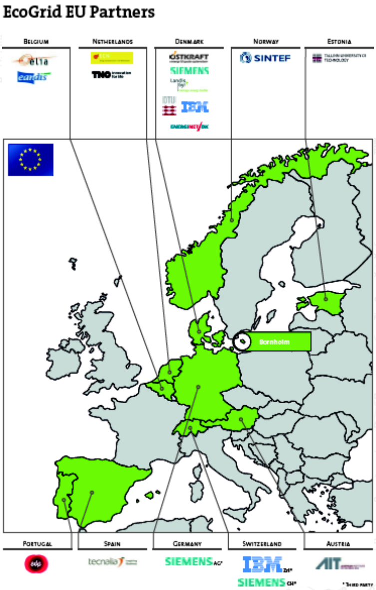




- **The unfortunate paradox:** under current market design (even with natural improvements), it is most likely that optimal strategies would be simply not offer/provide any service at all!
- Again here, how could this be changed?

Soares T, Pinson P, Jensen TV, Morais H (2015) Optimal joint offering strategies for wind in energy and primary reserve markets. *under review*

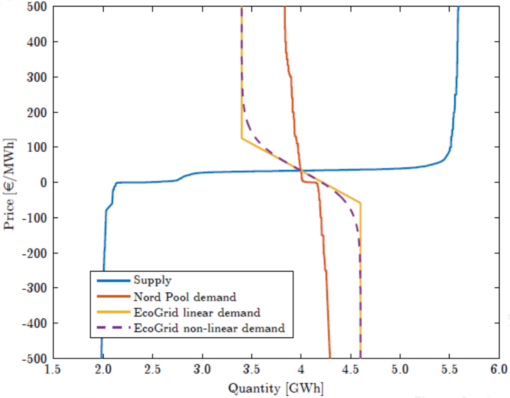
Demand response in EcoGrid EU



Key aspects:

- Nearly 1900 households/commercial/industry installations participating
- Design and evaluation of a complete market concept
- Commitment from academia and relevant industry partners, e.g., Energinet, Østkraft, IBM, Siemens, etc.
- A lot of sweat and stress...

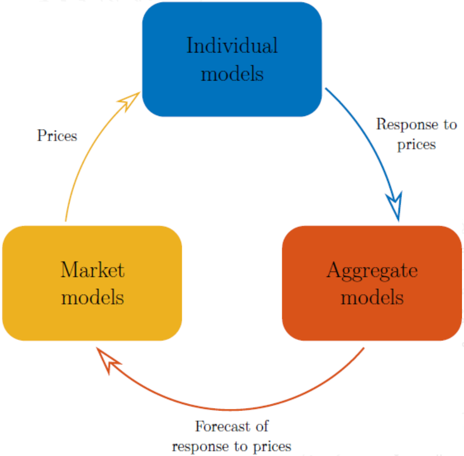
Demand-response: the elastic demand background



- The market itself:
  - An additional market aiming to mobilize demand-side flexibility (near) real-time
  - Demand is then enabled as a service provider, e.g., for balancing or congestion management
  - Demand is part of a pool among other potential service providers

- Important considerations on the demand side:
  - The approach should scale nicely, and directly reward demand for its flexibility
  - However, such an approach relies on the conditional dynamic elasticity of electricity consumers
  - Forecasting it is key, and even then the actual response may still be uncertain

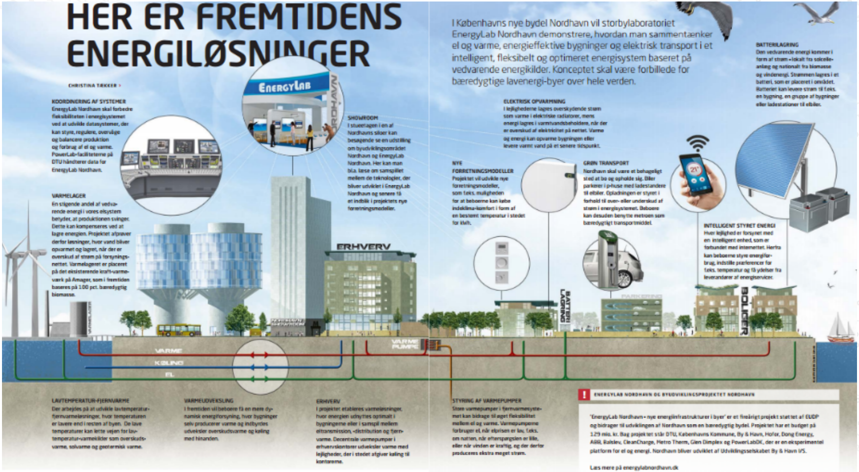
EcoGrid EU: The resulting market concept



- A few personal thoughts:
    - Some might say that this is a "twisted" market, since demand never offered its flexibility
    - The concept is packed with analytics concepts - it could be very sensitive to the quality of models employed

Towards the future in København...

EnergyLab Norhavn



HER ER FREMTIDENS ENERGILØSNINGER

CHRISTINA TÆKKER >

I Københavns nye bydel Nordhavn vil storbylaboratoriet EnergyLab Nordhavn demonstrere, hvordan man sammentænker el og varme, energieffektive bygninger og elektrisk transport i et intelligent, fleksibelt og optimeret energisystem baseret på vedvarende energikilder. Konceptet skal være forbillede for bæredygtige lavenergi-byer over hele verden.

KOORDINERING AF SYSTEMER
EnergyLab Nordhavn skal forbedre fleksibiliteten i energisystemet ved at udvikle datasystemer, der kan styre, regulere, overvåge og balancere produktion og forbrug af el og varme. PowerLab-faciliteterne på DTU håndterer data for EnergyLab Nordhavn.

SHOWROOM
I stueetagen i en af Nordhavns siloer kan besøgende se en udstilling om byudviklingsområdet Nordhavn og EnergyLab Nordhavn. Her kan man bl.a. læse om samspillet mellem de teknologier, der bliver udviklet i EnergyLab Nordhavn og senere få et indblik i projektets nye forretningsmodeller.

VARMELAGER
En stigende andel af vedvarende energi i vores elsystem betyder, at produktionen svinger. Dette kan kompenseres ved at lagre energien. Projektet afprøver derfor løsninger, hvor vand bliver opvarmet og lagret, når der er overskud af strøm på forsyningsnettet. Varmelageret er placeret på det eksisterende kraft-varmeværk på Amager, som i fremtiden baseres på 100 pct. bæredygtig biomasse.

ELEKTRISK OPVARMNING
I lejlighederne lagres overskydende strøm som varme i elektriske radiatorer, mens energi lagres i varmtvandsbeholdere, når der er overskud af elektricitet på nettet. Varme og energi kan opvarme bygningen eller levere varmt vand på et senere tidspunkt.

BATTERILAGRING
Den vedvarende energi kommer i form af strøm – lokalt fra solcelleanlæg og nationalt fra biomasse og vindenergi. Strømmen lagres i et batteri, som er placeret i området. Batteriet kan levere strøm til f.eks. en bygning, en gruppe af bygninger eller ladestationer til elbiler.

NYE FORRETNINGSMODELLER
Projektet vil udvikle nye forretningsmodeller, som f.eks. muligheden for at beboerne kan købe indeklima-komfort i form af en bestemt temperatur i stedet for kWh.

GRØN TRANSPORT
Nordhavn skal være et behageligt sted at bo og opholde sig. Biler parkerer i p-huse med ladestandere til elbiler. Opladningen er styret i forhold til over- eller underskud af strøm i energisystemet. Beboere kan desuden benytte metroen som bæredygtigt transportmiddel.

INTELLIGENT STYRET ENERGI
Hver lejlighed er forsynet med en intelligent enhed, som er forbundet med internettet. Herfra kan beboerne styre energiforbrug, indstille præferencer for f.eks. temperatur og få ydelser fra leverandører af energiservicer.

LAVTEMPERATUR-FJERNVARME
Der arbejdes på at udvikle lavtemperatur-fjernvarmeløsninger, hvor temperaturen er lavere end i resten af byen. De lave temperaturer kan lette vejen for lavtemperatur-varmekilder som overskudsvarme, solvarme og geotermisk varme.

VARMEUDVEKSLING
I fremtiden vil beboere få en mere dynamisk energiforsyning, hvor bygninger selv producerer varme og indbyrdes udveksler overskudsvarme og køling med hinanden.

ERHVERV
I projektet etableres varmeløsninger, hvor energien udnyttes optimalt i bygningerne eller i samspil mellem eltransmission, -distribution og fjernvarme. Decentrale varmepumper i erhvervskontorer udveksler varme med lejligheder, der i stedet afgiver køling til kontorerne.

STYRING AF VARMEPUMPER
Store varmepumper i fjernvarmesystemet kan bidrage til øget fleksibilitet mellem el og varme. Varmepumperne forbruger el, når elprisen er lav, f.eks. om natten, når efterspørgslen er lille, eller når vinden er kraftig, og der derfor produceres ekstra meget strøm.

! ENERGYLAB NORDHAVN OG BYUDVIKLINGSPROJEKTET NORDHAVN

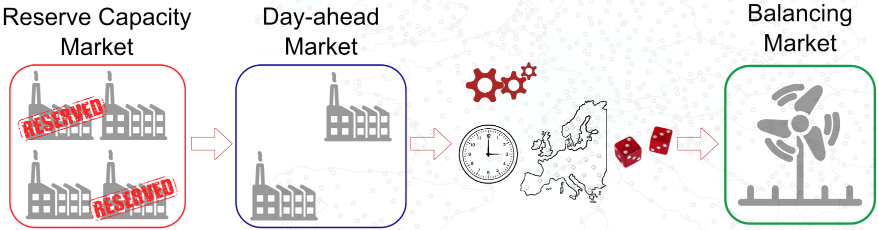
'EnergyLab Nordhavn – nye energiinfrastrukturer i byer' er et fireårigt projekt støttet af EUDP og bidrager til udviklingen af Nordhavn som en bæredygtig bydel. Projektet har et budget på 129 mio. kr. Bag projektet står DTU, Københavns Kommune, By & Havn, Hofor, Dong Energy, ABB, Balslev, CleanCharge, Metro Therm, Glen Dimplex og PowerLabDK, der er en eksperimentel platform for el og energi. Nordhavn bliver udviklet af Udviklingsselskabet By & Havn I/S.

Læs mere på energylabnordhavn.dk

... And hopefully soon **EcoGrid 2.0**!

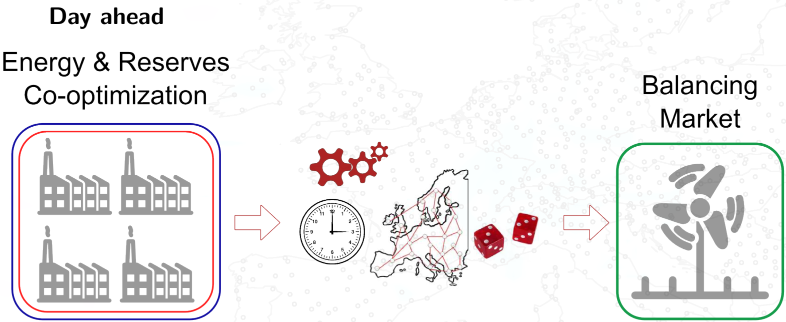
HVDC coordination - market-based exchange as of today

- Due to uncertainties in renewable energy generation, load, etc., we need to
  - **Quantify necessary reserves** to handle discrepancies between day-ahead schedule and actual dispatch
  - **Optimize available transmission capacity** between market zones



Area requirements

- Considering **HVDC links between market areas**, a better approach may be to
  - Quantify necessary reserves **jointly for all areas**
  - **Optimize usage of HVDC links** for day-ahead schedule, and reserved for real-time balancing

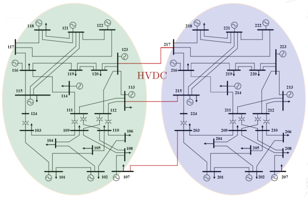


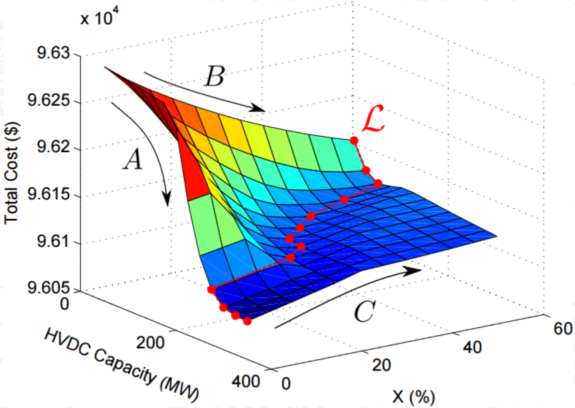
Delikaraoglou S, Pinson P, Eriksson R, Weckesser T (2015) Optimal dynamic capacity allocation of HVDC interconnections for cross-border exchange of balancing services in presence of uncertainty. Arxiv.org/abs/1503.00195

The optimal HVDC allocation problem

How much of the HVDC link should we use when clearing the day ahead market, and reserve for balancing market operations?

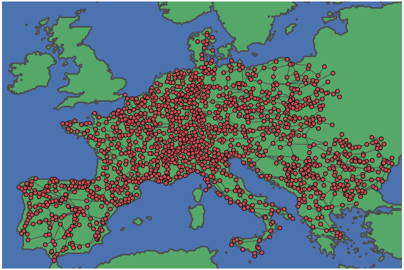
Example system setup

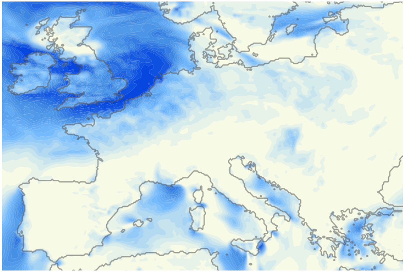


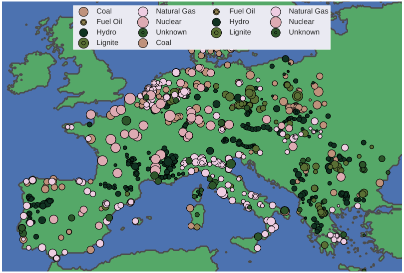


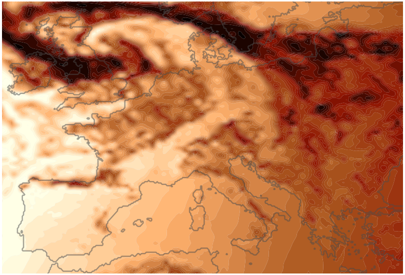
Give us more data!

Let us build a (very) large-scale dataset for the whole European system





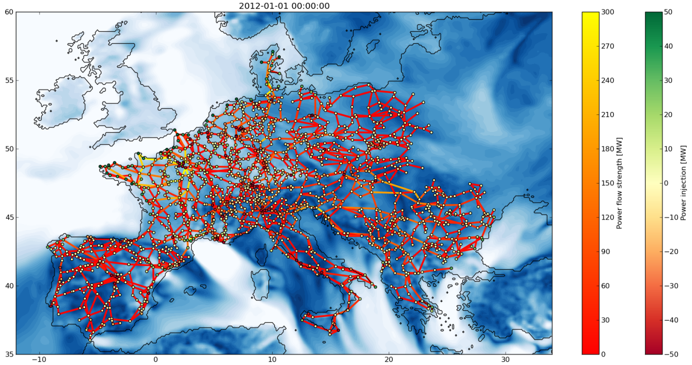




Available (after some IPR details to be settled...) for research purpose only!

The big picture...

- The **"grand forecasting challenge"**: predict *renewable power generation*, *dynamic uncertainties* and *space-time dependencies* at once for the whole Europe...!



- **Linkage with future electricity markets:**
  - Monitoring and forecasting of the complete **"Energy Weather"** over Europe
  - Provides all necessary information for coupling of various existing markets (e.g., day-ahead, balancing), and deciding upon optimal cross-border exchanges

Outlook

- There is **still so much to be done in this field!** E.g.,
    - understanding the impact of renewables on electricity markets, players, investment, and overall social welfare
    - accommodating it through appropriate market design, market participation strategies, demand response, coupling of electricity with other energy carriers, etc.
    - simply better understand and predict wind (/solar) power generation...
    - etc.

- Strategically we see **our role is**
    - to support industry and policy makers in a fast-changing environment
    - to focus on a wealth of relevant (though difficult) mathematical problems related to integration of renewables in power systems through market mechanisms

Thanks for your attention!