Using stochastic programming to analyse demand response in European electricity markets

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Post doc, Dept. of industrial economics

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PhD student, Dept. of industrial economics
Outline

• Transition to near zero emission power systems
• The EMPIRE model
  • Multi-horizon stochastic programming
• European technology mix
  • EMPIRE case 1: passive consumers
• The active consumer
  • Models for scheduling and bidding
• European technology mix
  • EMPIRE case 2: active consumers and demand response
• References
The Zero Emission Power system

What is needed to achieve 90% emission cuts in 2050?

• Transmission versus storage

• How does the role of gas develop
  • With CCS?
  • Or without.

• The “winter package”: Active consumers and demand response. An alternative to transmission?
Backdrop: European Commission's view of a low-carbon Europe

Figure 1: EU GHG emissions towards an 80% domestic reduction (100% = 1990)

Today: almost 25% of total emissions from power generation

Zero Emission Power systems

- Analyses using the EMPIRE model
- Power system design and operation
  - Time horizon until 2050 – investments in 5 year steps
  - Model operational time periods: demand, supply (stochastic wind and solar PV) and optimal dispatch.
- Provides a cost minimization capacity expansion plan for Europe, detailed for each country
EUROPEAN MODEL FOR POWER SYSTEM INVESTMENT WITH RENEWABLE ENERGY (EMPIRE)

Modeling assumptions
- Perfect competition (system cost minimization formulation)
- Inelastic demand
- Generation capacity aggregated per technology (i.e. do not model individual plants)
- Investments are continuous
- Lines are independent (i.e. transportation network)
- Perfect foresight about fuel prices, carbon price, and load development.
The challenge for Zero Emission Power Systems - Intermittent generation and variable load
We need to model variations in wind, both the intermittent nature and geographically.

**Figure**: ECMWF wind field data for Europe (source: European Environment Agency)
We need to model variations in solar irradiation, both the intermittent nature and geographically.

Figure: Average solar irradiation in Continental Europe (source: solargis)
CO-OPTIMIZATION OF STRATEGIC AND OPERATIONAL DECISIONS

Optimal investment strategy 2010-2015

Coupled optimization problem to minimize total system costs

Optimal dispatch for representative 168-hour blocks
Multi-stage, Multi-Scale Stochastic Programming (SP)

Uncertainty types

- Strategic examples
  - Investment cost
  - Carbon price
  - Fuel price development
- Operational examples
  - Load levels
  - Intermittent RES generation
  - Hydro reservoir inflow

Legend

- Investment (strategic) decisions
- Operational decisions

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LOOSE COUPLING HERE-AND-NOW OPERATION AND FUTURE DECISIONS

- Future strategic and operational uncertainty independent of current (operational) information
  - Example: observing current wind generation does not give you updated information about future weather

- Future strategic and operational decisions independent of current operational decisions
  - Example: current output from your CCGT does not impact what is optimal to do (investments, operation) in the future
MULTI-HORIZON STOCHASTIC PROGRAMMING (SP)

Important assumptions

- Strategic uncertainty independent of operational uncertainty
- Here-and-now operation does not impact future
  - Strategic decisions
  - Operational decisions

Reduces tree size by a factor of $(\# \text{ of nodes})^{\# \text{ of strategic periods}}$

PERFECT FORESIGHT IN THE LONG-TERM

Common setting if the goal is to analyze system transition for a pathway scenario

Legend
Investment (strategic) decisions ○
Operational decisions □
EMPIRE STOCHASTIC PROGRAMMING MULTI-HORIZON STRUCTURE

\[ x_i: \text{investments in period } i (2015, 2020, \ldots, 2050) \]
\[ y_{i\omega}: \text{Operational variables (dispatch, flows, etc.) period } i, \text{stochastic scenario } \omega \]

Mathematical formulation of EMPIRE

\[
\min_{\mathbf{x} \in \mathbb{R}^n} Q(\mathbf{x}) = \sum_{i=1}^{I} \delta_i \left\{ \mathbf{c}_i^T \mathbf{x}_i + \sum_{\omega \in \Omega_i} p_{\omega i} Q_{\omega i}(\mathbf{x}_{1:i}) \right\}, \text{ s.t. } A\mathbf{x} = \mathbf{b}, \mathbf{x} \geq 0,
\]

\[
Q_{\omega i}(\mathbf{x}_{1:i}) = \min_{\mathbf{y}_{\omega i} \in \mathbb{R}^m} \left\{ \mathbf{q}_i^T \mathbf{y}_{\omega i} \mid W_i \mathbf{y}_{\omega i} = h_{\omega i} - T_{\omega i} \mathbf{x}_{1:i}, \mathbf{y}_{\omega i} \geq 0 \right\}.
\]
OPERATIONAL OPTIMIZATION – TEMPORAL STRUCTURE
OPERATIONAL DATA – SLICING

Load

Wind profile

Solar profile
SAMPLE SCENARIOS
Background
Scenario assumptions

1. Baseline decarbonization: 90% emission reduction from 2010 to 2050
   i. Grid expansion towards 2020 fixed to ENTSO-E’s 2016 TYDP reference capacities.
      i. Beyond 2020: expansion limit of 4 GW for each interconnector every five year period
   ii. Capacity limits for selected technologies
      i. Wind onshore capacity potential from IEA’s NETP 2016.
      ii. Solar limited to cover no more than 14% of a country’s area (assuming 150 W/m²)
      iii. Nuclear capacities limited
   iii. RES targets defined for Germany, France, Great Britain and Spain
   iv. Development of Norwegian hydro power predefined

2. Alternative scenario NoCCS: same as baseline but no carbon capture and storage available
Medium optimistic assumptions for “decentral” technologies


Baseline scenario: 90% emission reduction

<table>
<thead>
<tr>
<th>Technology/fuel (2050)</th>
<th>Capacity [GW]</th>
<th>Generation [TWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>954 (46%)</td>
<td>1026 (26%)</td>
</tr>
<tr>
<td>Wind</td>
<td>503 (24%)</td>
<td>1057 (27%)</td>
</tr>
<tr>
<td>Gas CCS</td>
<td>204 (10%)</td>
<td>1043 (26%)</td>
</tr>
<tr>
<td>Coal CCS</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Fossil unabated</td>
<td>233 (11%)</td>
<td>231 (5%)</td>
</tr>
<tr>
<td>Others</td>
<td>166 (8%)</td>
<td>578 (15%)</td>
</tr>
</tbody>
</table>

Battery energy storage by 2050: 99 GWh
NoCCS scenario: 90 % emission reduction

<table>
<thead>
<tr>
<th>Technology/fuel (2050)</th>
<th>Capacity [GW]</th>
<th>Generation [TWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>1001 (46%)</td>
<td>1120 (28%)</td>
</tr>
<tr>
<td>Wind</td>
<td>623 (28%)</td>
<td>1284 (32%)</td>
</tr>
<tr>
<td>Gas CCS</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Coal CCS</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Fossil unabated</td>
<td>247 (11%)</td>
<td>371 (9%)</td>
</tr>
<tr>
<td>Others</td>
<td>316 (15%)</td>
<td>1204 (30%)</td>
</tr>
</tbody>
</table>

Battery energy storage by 2050: 339 GWh
Transition to a low-carbon European power sector

Increased shared of unabated natural gas in the medium term. Due to:
- Retirement of nuclear and coal
- Increasingly restrictive carbon constraints
- Still high RES costs

Solar investments start taking off by 2030. Cost drop below 500 €/kW

Natural gas still has a role in the mix towards 2050. With CCS: one third of the energy mix. Without CCS: less than 10%
Baseline country results 2050

Source: CenSES position paper Norway as a flexibility provider to Europe, in preparation.
NoCCS country results 2050

Source: CenSES position paper Norway as a flexibility provider to Europe, in preparation.
Transmission

- **Baseline**
  - European cross-boarder interconnector expansion: capacity increases by 644% from 2010 to 2050

- **NoCCS**
  - Capacity increases by 826% from 2010 to 2050
# Selection of flexibility options 2050

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Baseline</th>
<th>NoCCS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gas (GW)</td>
<td>Trans. (GW)</td>
</tr>
<tr>
<td>With transmission exp.</td>
<td>398</td>
<td>416</td>
</tr>
<tr>
<td>Limited transmission exp.</td>
<td>442</td>
<td>121</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Baseline</th>
<th>NoCCS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Curtail energy (TWh/an)</td>
<td>Avg. elec. Cost (€/MWh)</td>
</tr>
<tr>
<td>With transmission exp.</td>
<td>60</td>
<td>51</td>
</tr>
<tr>
<td>Limited transmission exp.</td>
<td>83</td>
<td>54</td>
</tr>
</tbody>
</table>
Alternatives to transmission

FIRST CONCLUSION:
There is a high need for flexibility in the future system
In the studies I have shown, transmission investment seems to be the solution.

NEW DRIVERS:
- Demand side flexibility
- The merger of the power system and ICT

How will this affect the transition to a near zero emission power system?
Changes in the electricity market

• New contract types and business models
  • Complex and dynamic price models
  • Penalization for peaks (demand charges)
  • Reward from providing flexibility

• Market participant changes
  • Passive consumer => flexible prosumer
  • New-comers: Energy Service Companies (ESCo), Aggregators ++

• New markets and changes in market rules
  • More focus on (close to) real time
  • Local markets
Challenge: “Trouble in the neighbourhood”
Active interaction between smart end users and the energy system/market to create benefits in the value chain

Demand side flexibility

Why this flexibility has an increasing value
  - New distributed renewable energy generation
  - Electric vehicles creating peak problems

Local challenges must be met by local solutions

Need proper decision models
A stochastic model for scheduling energy flexibility in buildings

• Context: A prosumer in the end-user market
• Problem: How to schedule flexible units to minimize total energy-related costs?
• Develop a basic model for demand side flexibility used throughout the thesis
  • Load units classified according to their flexibility properties:
    • Shiftable (in time)
      • Profile: Start time can be changed, but profile must be kept
      • Volume: Profile can be altered
    • Curtailable
      • Reducible: Load can be reduced without disconnection
      • Disconnectable: On or off
    • Inflexible
Optimization model

• Objective: Minimize expected total costs

\[
\min z = \sum_{s \in S} R_s \cdot \left[ \sum_{a \in A \atop t \in T} P^\text{energy}_{a,t,s} \chi_{a,t,s}^{\text{net-in}} + \sum_{a \in A} P^\text{cap}_a \chi_{a,s}^{\text{cap}} + \sum_{y \in Y \atop o \in O \atop t \in T} \alpha_{o,y,t,s}^{\text{start}} G_{y,o}^{\text{startup}} + \right. \\
\left. \sum_{d \in D \atop y \in Y \atop t \in T} X_{d,y,t} \varphi_{d,y,t,s} - \sum_{a \in A \atop t \in T} P^\text{sales}_{a,t} \chi_{a,t,s}^{\text{net-out}} \right]
\]

• Subject to:
  – Energy source constraints
  – Converter constraints
  – Storage constraints
  – Load constraints
  – Energy system balances

• Stochastisk mixed integer problem (SMIP)
Demand response as a technology in EMPIRE

Demand Response module in EMPIRE: in testing now

Multiscale geographical representation
  • Countries
  • Regions
  • Neighbourhoods

Kilde: 3M, Smart Grid: http://solutions.3m.com/wps/portal/3M/en_EU/SmartGrid/EU-Smart-Grid/

How does it change the technology mix?
Demand Response (DR) module

<table>
<thead>
<tr>
<th>DR Potential</th>
<th>Aggregated per Country</th>
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</thead>
<tbody>
<tr>
<td>Flexible Load Types</td>
<td>7</td>
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<tr>
<td>Economic Sectors</td>
<td>3</td>
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<tr>
<td>Load Profiles</td>
<td>Standard Deterministic</td>
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<td>Investment Steps</td>
<td>5 years</td>
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<tr>
<td>Operation Steps</td>
<td>Standard Hourly Periods</td>
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<tr>
<td>Shiftable Volume Load</td>
<td>✓</td>
</tr>
<tr>
<td>Curtailable Load</td>
<td>✓</td>
</tr>
</tbody>
</table>
### DR costs characteristics

<table>
<thead>
<tr>
<th>Technology</th>
<th>Investment Cost (€/kW)</th>
<th>Fixed OM (€/kW) pr. yr.</th>
<th>Variable OM (€/MWh)</th>
<th>Efficiency</th>
<th>Fuel Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>HeatingAC</td>
<td>250</td>
<td>7.50</td>
<td>10</td>
<td>0.97</td>
<td></td>
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<tr>
<td>HVAC-ComInd</td>
<td>10</td>
<td>0.30</td>
<td>5</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>CoolingWater-ComInd</td>
<td>5</td>
<td>0.15</td>
<td>20</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>ProcessShift-Ind</td>
<td>0</td>
<td>0.00</td>
<td>150</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>WashingEq-Res</td>
<td>30</td>
<td>0.90</td>
<td>50</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>StorHeat-ResCom</td>
<td>20</td>
<td>0.60</td>
<td>10</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Process Shed-Ind</td>
<td>0</td>
<td>0.00</td>
<td>1000</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Battery Storage (Li-ion)</td>
<td>1195</td>
<td></td>
<td></td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>Battery Storage (Zn)</td>
<td>588</td>
<td></td>
<td></td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Pumped Storage Hydro</td>
<td>1000</td>
<td></td>
<td></td>
<td>0.80</td>
<td></td>
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<tr>
<td>Gas CCGT</td>
<td>650</td>
<td>30.38</td>
<td>0.45</td>
<td>42</td>
<td></td>
</tr>
</tbody>
</table>
DR capacity evolution (GW)
Summer Load Week Sample in Spain 2050 (GW)
Summer Load 2-day Sample in Spain 2050 (GW)

- Wind Production
- Solar Production
- Original Residual Load
- New Residual Load
Capacities comparison between DR2 and DR0

- The following bar graphs show the main differences in technology capacities in the case with DR (case DRB) and without (case DR0) between year 1 (2010) and year 9 (2050).
- The positive y-axis indicate larger capacity in DRB than in DR0 and viceversa
Europe's peak plants capacity differences (GW)

- Gas ex.
- OCGT
- CCGT
- Gas CCS

DR Baseline

DR0
Europe's peak plants generation differences (TWh)

- Gas ex.
- OCGT
- CCGT
- Gas CCS

DR Baseline

DR0
Europe's coal capacity differences (GW)
Europe's coal generation differences (TWh)

- Lignite ex.
- Lignite
- Lignite CCS
- Coal ex.
- Coal
- Coal CCS

DR Baseline

DR0
Europe's IRES capacity differences (GW)

- Onshore Wind
- Offshore Wind
- Solar

DR Baseline
DR0
Europe's IRES generation differences (TWh)

- Onshore Wind
- Offshore Wind
- Solar

DR Baseline
DR0
Storage Energy Differences (GWh)

- Pump Hydro Storage
- Battery Storage

DR Baseline
DR0
Summary

• New technologies increase the need for flexibility at different levels
• New technologies increase the potential for flexibility provision from demand side
• Flexibility can create values at different levels (prosumer, DSO, TSO…)
• Aggregation needed
• The aggregator’s decision problem is a complex task
• Demand response will put pressure on other technologies, both transmission and other flexibility sources.
References

• EMPIRE


• **MULTI-HORIZON & SCENARIOS**


Demand response and the aggregator role

• Hector Marañón-Ledesma, Asgeir Tomaszgard, Christian Skar, Long-Term Electricity Investments Accounting for Demand and Supply Side Flexibility, in progress.

• Ottesen, Stig Ødegaard; Tomaszgard, Asgeir; Fleten, Stein-Erik, *Multi market bidding strategies for demand side flexibility aggregators in electricity markets*, in review process. Working paper can be downloaded.


• Stig Ø. Ottesen & Asgeir Tomaszgard, A stochastic model for scheduling energy flexibility in buildings, Energy, vol 88, 2015
TACEMM winter school Energy market modelling
March 3-8 Kvitfjell, Norway

• Integrating economics, engineering, mathematics and optimization to address issues arising in the energy markets of today and the future
• Models for long-term and short-term analysis of energy systems and markets
• Optimization and equilibrium models
• Applications of stochastic optimization

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NTNU
NTNU
NHH
Energy Transition Week in Trondheim, 25-29 March 2019

• 25 March: Workshop on hydropower and its interplay with other renewables and market design
• 26 March: Energy transition conference
• 27 March: Technoport conference
• 28 March: Workshop on energy system integration and future markets
• 29 March: Workshop on decarbonizing industry
• July 29 - August 2: The ICSP conference Trondheim
  The conference includes parallel sections, plenary talks from leading researchers in stochastic optimization and a set of mini symposia, featuring a semi-plenary followed by a stream of recent contributions on selected state-of-the-art topics. There will be an opening reception on the evening of the 28th. See full list of accepted mini-symposia here: https://www.ntnu.edu/web/icsp/minisymposia. The call for contributed papers is now open: https://www.ntnu.edu/web/icsp/abstracts.

• July 27 and 28: Pre-conference tutorials
  A two-day introductory series of Tutorials precedes the main conference to provide introduction to some of the central research areas in Stochastic Programming.

• July 22 - July 26: PhD level introduction course in stochastic programming
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