Congestion Management through Topological Corrections: A Case Study of Europe

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LBNL-UC Berkeley DR/R/ISO Discussion Group
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EU Energy Policy

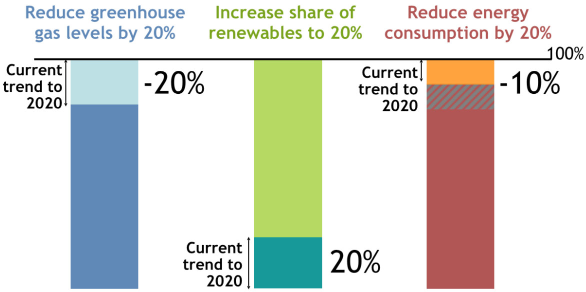
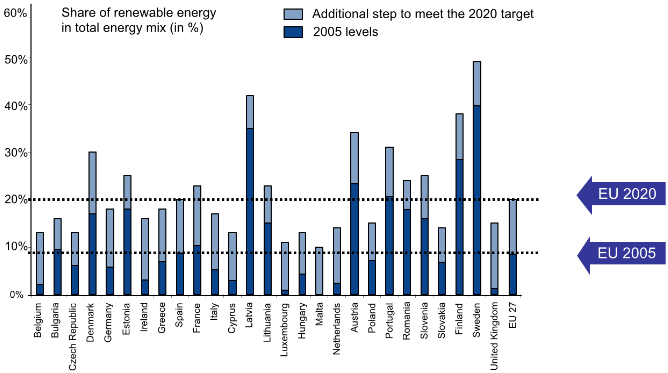


Figure: EU 2020 targets

- Ambitious EU environmental targets: Renewable Energy Directive (2009), Roadmap 2050 (2011), Energy Efficiency Directive (2011), ETS Directive (2013)

Renewable Energy Integration



Source: Renewable Energy Directive (2009)

- Renewable targets vary widely (10% - 49%, depending on the country), resulting in significant needs for cross-border power transfers
- Cross-border capacities should double on average by 2030 to accommodate renewable energy (ENTSO-E)

Renewable Energy Integration

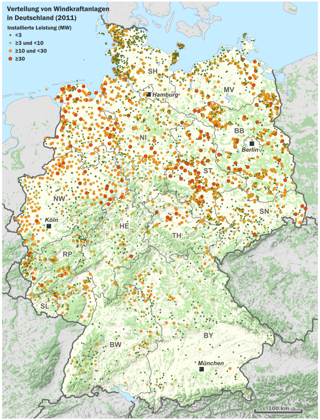


Figure: Wind farms in Germany (mostly in the northern part, while load is mainly located in the mid-western and southern part)

- Renewable resources are commonly located far from load centers, resulting in an increase of network congestion

Transmission Network Control

- Active control of the transmission network could provide economically and institutionally acceptable technological means towards overcoming operational challenges imposed by renewable integration
- Especially relevant in Europe due to the separation of the energy market from the operation of the transmission network
- FACTs devices, phase shifting transformers, tap changing transformers, HVDC lines, dynamic monitoring and adjustment of thermal line ratings, topological corrections (transmission line switching)

Transmission Topology Control

- Congestion caused by Kirchhoff's laws can be reduced by switching out transmission lines
- The role of topology control has been recognized as a corrective control in the case of contingencies, applied on an ad hoc basis (e.g. Belgian TSO, ELIA)

Transmission Topology Control

- Recent increase of computational capabilities enables systematic approach to topology control
  - Fisher et al. (2008): First mixed integer program formulation
  - Hedman et al. (2010): Co-optimization of unit commitment and topology control subject to N-1 reliability
  - Hedman et al. (2011): Topology control on industrial scale instance (New York ISO)
- European context
  - Kunz (2013): Transmission switching as a congestion alleviation method in Germany under high share of intermittent renewable generation
  - Villumsen et al. (2013): Impact of transmission switching on the optimal expansion of Danish transmission network in order to integrate 50% wind power

Scope of Our Work

- Quantify the impacts of topology control under the current European market regime (day-ahead market + balancing market) and a nodal pricing regime (hypothetical in Europe)
- Full consideration of unit commitment, provision of reserves and topology control
- High fidelity models of Europe
  1. Central Western Europe (CWE): 3188 buses, 4085 lines and 1095 generators
  2. Entire European system: 6584 buses, 8799 lines and 2059 generators

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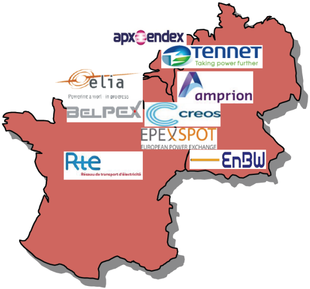
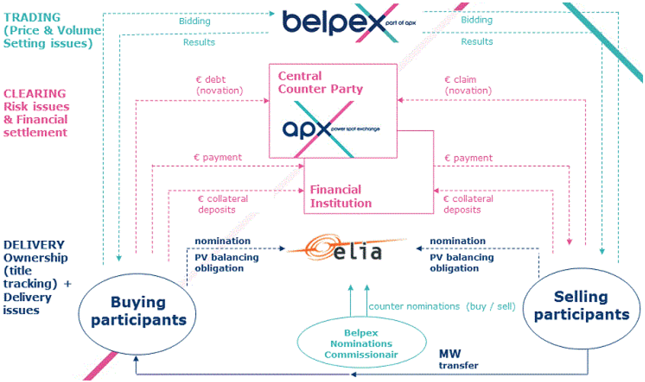
CWE Market Coupling



- CWE market coupling was launched in November, 2010, and includes the Belgian, Dutch, French and German electricity markets

Separation of Energy and Transmission

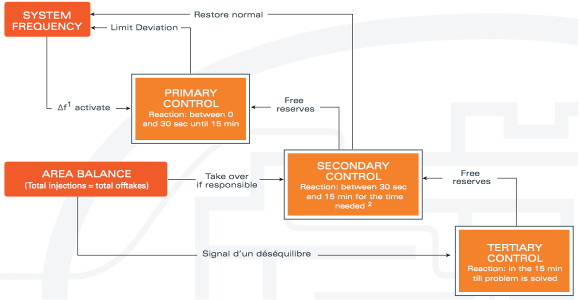


- Belpex day-ahead market is coupled to other day-ahead markets in the CWE region
- Electricity is delivered the day after via the Belgian transmission system operator ELIA

Day-Ahead Operations

- Power Exchange
  - Order accumulation (00h30-12h30), publication of market results (14h45 at the latest)
  - Double-sided uniform price auction
  - Spot orders and block orders
- Cross-Border Flows
  - Flows are represented via transportation model
  - The limits of the interconnection capacity (NTC) are determined by the system operators of the concerned markets
  - Capacity allocated by market coupling auction algorithm
- Reserve Market
  - Reserves used to
    - resolve imbalances and
    - resolve congestion
  - Reserve bids are submitted by 14h00 on the day ahead

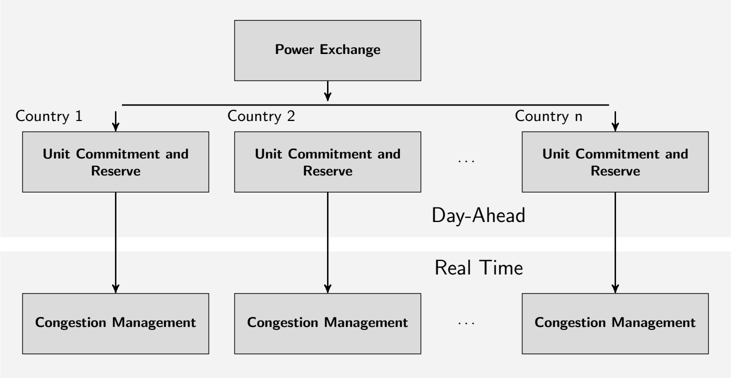
Real-Time Congestion Management



- Light overloads are acceptable for a short duration
- Topological modification of the grid is performed in order to restore short-term balance (0 - 15 minutes)
- Tertiary control is activated on the longer term (15 minutes - 8 hours)

Contents

Market Coupling Model



Day-Ahead Power Exchange Model

- Welfare maximization problem, where the transmission network is represented using a transportation model
- Transfers between adjacent countries are restricted by the net transfer capacity (NTC)
- Block orders are represented though unit commitment variables

Day-Ahead Power Exchange Model

$$\textbf{min} \sum_g \sum_t C_g p_{gt}$$ Minimize generation costs

$$\sum_{k \in \delta_n^-} f_{kt} - \sum_{k \in \delta_n^+} f_{kt} + \sum_{g \in g_n} p_{gt} + r_{nt} = D_{nt}, \ \forall n, t,$$ Flow conservation

$$r_{nt} \leq R_{nt}, \ \forall n, t,$$ Renewable production limit

$$p_{gt} \geq P_g^- u_{gt}, \ \forall g, t,$$ Min thermal generation

$$p_{gt} \leq P_g^+ u_{gt}, \ \forall g, t,$$ Max thermal generation

$$p_{gt} - p_{g,t-1} \leq R_g^+, \ \forall g, t,$$ Ramp up rate

$$p_{g,t-1} - p_{gt} \leq R_g^-, \ \forall g, t,$$ Ramp down rate

$$\sum_{k \in k_{c,cc}} f_{kt} \leq NTC_{c,cc}, \ \forall c, cc, t,$$ International flow limit

$$-TC_k \leq f_{kt} \leq TC_k, \ \forall k \in k_{c,cc}, \forall c, cc, t,$$ International line capacity

$$u_{gt} \in \{0, 1\}, \ \forall g, t.$$ Unit commitment decision

Day-Ahead Unit Commitment and Reserves Model

- Optimization of unit commitment schedules against day-ahead power exchange obligations and the provision of reserves
- Detailed consideration of unit commitment constraints
- The problem is solved by country, meaning that reserves are optimized separately within each control area, without coordination of cross-border reserve capacity

Day-Ahead Unit Commitment and Reserves Model

$$\textbf{min} \sum_{g \in G} \sum_{t} (C_g p_{gt} + K_g u_{gt} + S_g v_{gt})$$

Generation, startup, loading cost

$$\sum_{k \in \delta_n^-} f_{kt} - \sum_{k \in \delta_n^+} f_{kt} + \sum_{g \in g_n} p_{gt} + r_{nt}$$

$$+ \sum_{k \in \delta_n^- \cap k_*} \hat{f}_{kt} - \sum_{k \in \delta_n^+ \cap k_*} \hat{f}_{kt} = D_{nt}, \ \forall n, t,$$

Cross-border flow fixed

$$p_{gt} + rs_{gt} \leq P_g^+ u_{gt}, \ \forall g, t,$$

Provision of Reseves

$$\sum_{g \in g_c} rs_{gt} \geq RS_{t,c}^{req}, \ \forall t, c,$$

Reserve requirement

$$\sum_{q = t - UT_g + 1}^{t} v_{gq} \leq u_{gt}, \ \forall g, t \geq UT_g,$$

Min up time

$$\sum_{q = t+1}^{t + DT_g} v_{gq} \leq 1 - u_{gt}, \ \forall g, t \leq |T| - DT_g,$$

Min down time

$$v_{gt} \geq u_{gt} - u_{g,t-1}, \ \forall g, t,$$

Logical relation between u and v

$$v_{gt}, rs_{gt} \geq 0, \ \forall g, t,$$

$$u_{gt} \in \{0, 1\}, \ \forall g, t,$$

Unit commitment decision

$+$ Renewable production limit, Min thermal generation

$+$ Min and max ramping limit

Congestion Management Model

- In the real time, internal congestion is resolved by either resorting to the redispatch of generators, or to topological corrections, under physical network constraints
- In the case of redispatching, it is also allowed to start new fast generators that were determined to be offine at the day-ahead stage but can be brought online in short notice
- Contingency reserve decisions produced from higher level day-ahead unit commitment and reserves model are fixed in congestion management model

Congestion Management Model

$$\min \sum_g \sum_t C_g(p^+_{gt} - p^-_{gt}) + \sum_{g \in g_f} \sum_t (K_g u_{gt} + S_g v_{gt})$$

$$p_{gt} = \hat{p}_{gt} + p^+_{gt} - p^-_{gt}, \; \forall g, t,$$ Generation adjustment

$$\sum_{k \in \delta^-_n} f_{kt} - \sum_{k \in \delta^+_n} f_{kt} + \sum_{g \in g_n} p_{gt} + r_{nt} + \sum_{k \in \delta^-_n \cap k_*} \hat{f}_{kt} - \sum_{k \in \delta^+_n \cap k_*} \hat{f}_{kt} = D_{nt}, \; \forall n, t,$$ Cross-border flow fixed

$$r_{nt} \le R_{nt}, \; \forall n, t,$$ Renewable production limits

$$p_{gt} \ge P^-_g, \; \forall g \in g_{on}, t,$$ Constraints for on generators

$$p_{gt} \le P^+_g - \hat{rs}_{gt}, \; \forall g_{on}, t,$$ ...

$$p_{gt} - p_{g,t-1} \le R^+_g - \hat{rs}_{gt}, \; \forall g_{on}, t,$$ ...

$$p_{g,t-1} - p_{gt} \le R^-_g, \; \forall g_{on}, t,$$ ...

$$p_{gt} \ge P^-_g u_{gt}, \; \forall g \in g_f, t,$$ Constraints for fast generators

$$p_{gt} \le P^+_g u_{gt}, \; \forall g \in g_f, t,$$ ...

$$p_{gt} - p_{g,t-1} \le R^+_g, \; \forall g \in g_f, t,$$ ...

$$p_{g,t-1} - p_{gt} \le R^-_g, \; \forall g \in g_f, t,$$ ...

$$u_{gt} \in \{0, 1\}, \; \forall g \in g_f, t,$$ Commitment decision for fast generators

Congestion Management Model

Constraints on transmission control

$$f_{kt} - B_k(\theta_{mt} - \theta_{nt}) - M_k(1 - z_{kt}) \leq 0, \ \forall k = (m,n), t,$$

Kirchhoff's law active if a line is in service

$$-f_{kt} + B_k(\theta_{mt} - \theta_{nt}) - M_k(1 - z_{kt}) \leq 0, \ \forall k = (m,n), t,$$

...

$$-TC_k z_{kt} \leq f_{kt} \leq TC_k z_{kt}, \ \forall k, t,$$

Line flow capacity

$$\sum_k (1 - z_{kt}) \leq N, \ \forall t,$$

Max number of line switching

$$z_{kt} \in \{0,1\}, \ \forall k, t.$$

Binary line switching decision

- The problem is solved in two steps by sequentially solving the commitment of fast units and topology control
- In our experiment, we allow for at most 2-5 transmission line switches for each hour and at each country

Nodal Pricing Model

- The decentralized clearing of energy and reserves, followed by real-time congestion management, introduces scheduling as well as operating inefficiencies
- Compare the decentralized market clearing design to an integrated optimization of unit commitment, reserve commitment and topology control under physical network restrictions

Nodal Pricing Model

$$\textbf{min} \sum_{g}\sum_{t}(C_g p_{gt} + K_g u_{gt} + S_g v_{gt})$$

subject to Flow conservation constraints

Renewable production limits, Min and max thermal generation limits

Min and max ramping limits, Min up and down time limits

Reserve requirement,

Kirchhoff's laws, Line flow capacity

Line switching limits

- See Appendix for the formulation
- Since the model cannot be solved in one shot, we sequentially iterate among the following three subproblems: a dispatching subproblem, a unit commitment subproblem and a topology control subproblem

Contents

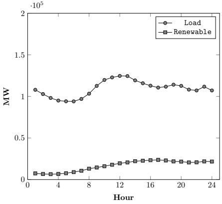
Power System

- Power system in the CWE region is taken from ENTSO-E System Study Model (STUM) representing the power system of continental Europe
- Consists of 5 countries, 3188 buses, 4085 lines and 1095 generators
- Full description of 380kV and 220kV transmission grid is used in the congestion management and nodal pricing model
- Two types of NTC are used in the day-ahead model
    - NTC type 1: Actual day-ahead NTC values in 2013 (from ENTSO-E)
    - NTC type 2: Sum of the physical interconnection capacities (approximately 50% greater than type 1 NTC)

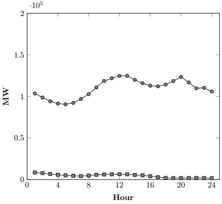
Load and Renewable Scenarios

High Renewables | Low Renewables

Low Load

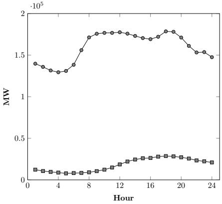


(a) June 1, 2013

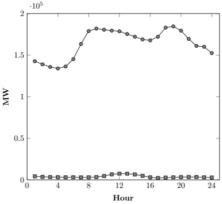


(b) October 5, 2013

High Load



(c) November 29, 2013



(d) December 10, 2013

Base Case (No Topology Control)

Table: Results of Base Case (1,000€, per day)

Model	Cost	06/01	10/05	11/29	12/05
MC1	Day-Ahead	32,940	44,573	63,359	81,484
	Congestion Management	1,603	1,337	1,121	1,184
	Total	34,544	45,910	64,480	82,669
MC2	Day-Ahead	32,136	43,899	62,519	80,488
	Congestion Management	1,804	1,545	1,192	1,015
	Total	33,940	45,445	63,712	81,504
NP	Total	32,417	44,093	62,606	80,315

- Congestion management costs amount to 1.24%-5.3% of total cost
- Transition to nodal pricing results in 2.8%-6.1% cost savings
- MC2 results in lower total costs but tends to result in higher congestion management costs

Base Case (No Topology Control)

- Congestion management is more costly when the load is relatively low (06/01 and 10/05 vs. 11/29 and 12/05)

Load	**Day-Ahead schedule**	**Real-time congestion management**
Low	Mostly base-load generators are committed	A considerable number of mid-merit power plants must be started, thereby resulting in costly congestion management
High	Many mid-merit generators are committed in addition to base-load units	TSO relies extensively on the online resources to resolve real-time congestion without starting up too many new generators

Cost Savings from Topology Control

Table: Cost Savings from Topology Control (1,000€, per day)

Model	Cost	06/01	10/05	11/29	12/05
MC1	Congestion Management	1,603	1,337	1,121	1,184
MC1+TC	Cost Savings from TC	1,219	1,162	895	1,113
	% Cost Savings	76.0%	86.9%	79.8%	94.0%
MC2	Redispatching Cost	1,804	1,545	1,192	1,015
MC2+TC	Cost Savings from TC	1,400	1,380	911	556
	% Cost Savings	77.6%	89.3%	76.4%	54.7%
NP	Total	32,417	44,093	62,606	80,315
NP+TC	Cost Savings from TC	291	156	265	160

- Daily cost savings achieved due to topology control are significant: 1.3%-3.5% of the total costs, which translate to €200-€500 million of annual savings
- Relative benefits of topology control are greater under market coupling: benefits are 0.2%-0.9% of total costs in nodal pricing

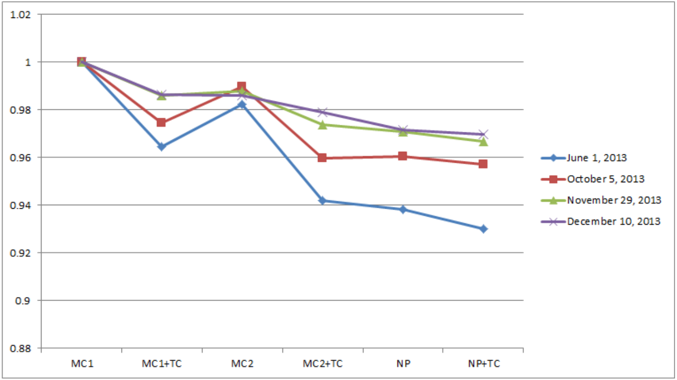
Congestion Management Costs

Table: Congestion Management Cost (€/MWh)

Model	06/01	10/05	11/29	12/05
MC1	0.61	0.51	0.29	0.30
MC1+TC	0.15	0.07	0.06	0.02
MC2	0.69	0.59	0.31	0.26
MC2+TC	0.15	0.06	0.07	0.12

- Congestion management costs amount to 0.26€/MWh - 0.69€/MWh
- Topology control reduces congestion management cost to 0.02€/MWh - 0.15€/MWh

Comparison of Different Models



- Comparing MC2+TC with NP: topology control yields comparable benefits to those that could be achieved by adopting nodal pricing

International Transfers

Table: Daily International Transfers (MWh)

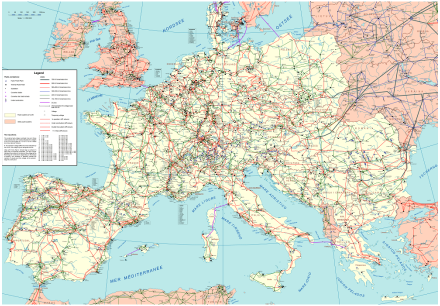
	06/01	10/05	11/29	12/05
MC1	197,107	194,192	162,526	139,676
MC2	288,980	263,350	218,718	166,297
NP	293,925	274,483	181,898	160,855
NP+TC	289,195	249,924	195,661	181,159

- Increasing NTC values and nodal pricing results in an increase of transfer volume, compared to MC1
- The effect of topology control in the volume of international transfers is not predictable (increase in trade in case of higher load)

Contents

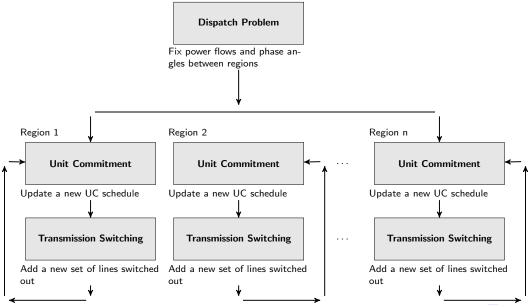
Power System

- Transmission network of continental Europe from ENTSO-E
- Consists of 25 countries, 6584 buses, 8799 lines and 2059 generators
- Each country is decomposed in regions (43 regions are considered in our experiments)



Decomposition Approach

- Dispatch problem is solved over the whole network to determine cross-border transfers
- Co-optimization problem of unit commitment and topology control is solved by region
- UC and TC are solved iteratively (5 times in our experiments, each iteration allows at most one line switching)

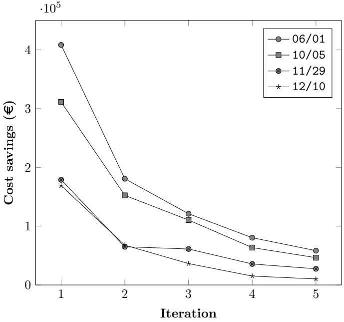


Cost Savings

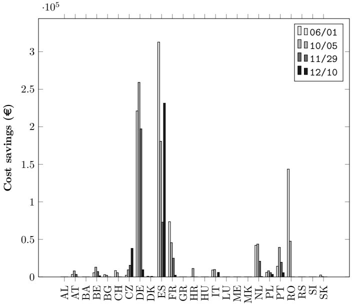
Scenario	Cost (€)	Base solution	TS solution	Savings	Scenario	Base solution	TS solution	Savings
06/01	Generation	29,545,240	28,758,644	786,596	11/29	57,799,454	57,636,496	162,958
	Min load	11,914,000	11,865,977	48,023		16,385,999	16,356,765	29,234
	Startup	176,898	174,512	2,386		842,508	835,249	7,259
	Load Penalty	133,341	121,214	12,127		866,388	697,406	168,981
	Total	**41,769,479**	**40,920,348**	849,131		**75,894,348**	**75,525,916**	368,432
10/05	Generation	39,108,312	38,673,415	434,897	12/10	78,366,354	78,256,510	109,844
	Min load	13,865,703	13,661,071	204,632		18,185,922	18,191,583	-5,661
	Startup	536,743	500,747	35,996		1,188,564	1,189,223	-659
	Load Penalty	667,006	658,275	8,732		1,037,902	842,839	195,063
	Total	**54,177,764**	**53,493,507**	684,257		**98,778,742**	**98,480,155**	298,587

- Daily savings due to topology control range between €0.30 million to €0.85 million, which amount to 0.30%-2.03% of the total cost (at most 5 line switches at each hour and for each region)
- Cost savings and switching actions decrease with higher net load

Cost Savings



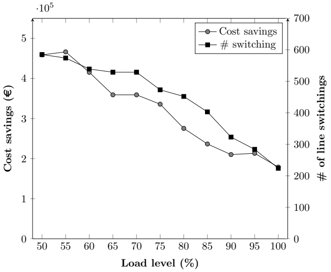
(e) Savings over iterations



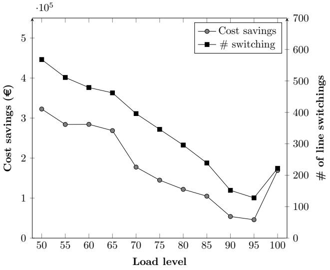
(f) Savings by country

- Additional iterations (switches) result in marginal benefits
- Germany, Spain and France benefit most from topology control

Sensitivity of Results on Load Level



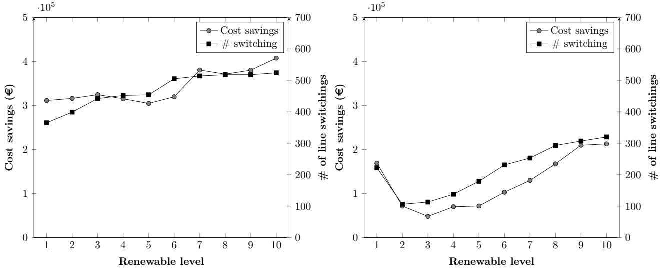
(g) November 29



(h) December 10

- Load level varies between 50% and 100% of original load
- Cost savings decrease as loading increases, especially relevant due to renewable integration
- Jump in cost savings (at 100% load) in December is due to prevention of load shedding
- Number of switching actions correlated to cost savings

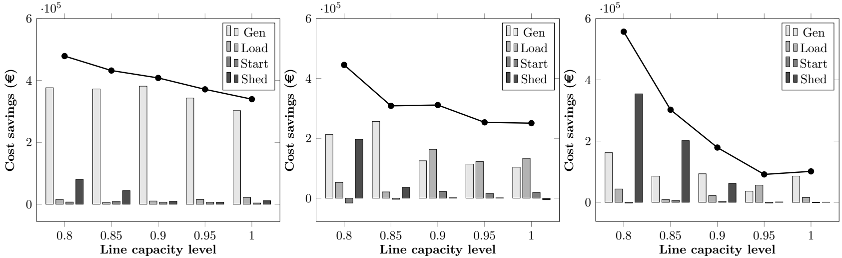
Sensitivity of Results on Renewable Supply



(i) October 5 (j) December 10

- Nominal renewable supply is amplified by 1-10 (up to 38% and 27% of total load)
- Cost savings tend to increase with the increase of renewables due to better utilization of ‘free’ renewable supply
- Number of switching actions correlated to cost savings

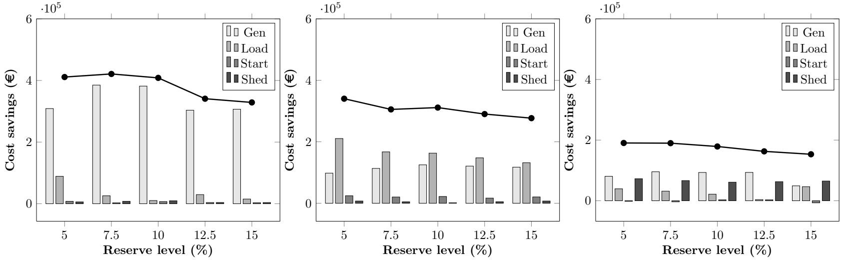
Sensitivity of Results on Line Capacity



(k) June 1 (l) October 5 (m) November 29

- Line capacity varies between 80% and 100% of original line capacity
- Cost savings tend to increase as line capacity decreases
- With the decrease of line capacity, load shedding increases and therefore cost savings from preventing load shedding increase

Sensitivity of Results on Reserve Level



(n) June 1 (o) October 5 (p) November 29

- Reserve level varies between 5% and 15% of total load
- Cost savings tend to increase as reserve level decreases

Contents

Conclusions

- In the CWE region:
  - congestion management costs amount to 1.24%-5.3% of total cost
  - transition to nodal pricing results in 2.8%-6.1% cost savings
  - daily cost savings achieved due to topology control are 1.3%-3.5% of total costs (€200-€500 million annual savings)
  - relative benefits of topology control are 0.2%-0.9% of total costs in nodal pricing
  - transmission switching can deliver comparable benefits to overhaul of European markets via transition to nodal pricing
- In the European continent at large:
  - daily savings due to topology control amount to 0.30%-2.03% of total cost (€300k-€850k)
  - benefits of transition switching diminish rapidly after 2-3 lines are switched per region
  - lower net load implies higher benefits from transmission switching, especially relevant due to renewable integration

Perspectives

- Transmission expansion planning
  - Eirgrid case study: bringing offshore wind power to Ireland
  - Brute-force All-Island model achieves 20% MIP gap after 1 week of running on CPLEX
- Endogenous modeling of uncertainty in a stochastic programming and Monte Carlo simulation framework
- Decomposition methods and parallel computing
  - (Binato, 2001): Benders decomposition
  - Intelligent sampling of representative operating days

Thank You

Questions?

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Presentation available in
http://perso.uclouvain.be/anthony.papavasiliou/public_html/

Appendix: Nodal pricing model formulation

$$\min \sum_g \sum_t (C_g p_{gt} + K_g u_{gt} + S_g v_{gt})$$

$$\sum_{k \in \delta_n^-} f_{kt} - \sum_{k \in \delta_n^+} f_{kt} + \sum_{g \in g_n} p_{gt} + r_{nt} = D_{nt}, \ \forall n,t,$$

$$r_{nt} \leq R_{nt}, \ \forall n,t,$$

$$p_{gt} \geq P_g^- u_{gt}, \ \forall g,t,$$

$$p_{gt} + rs_{gt} \leq P_g^+ u_{gt}, \ \forall g,t,$$

$$p_{gt} - p_{g,t-1} + rs_{gt} \leq R_g^+, \ \forall g,t,$$

$$p_{g,t-1} - p_{gt} \leq R_g^-, \ \forall g,t,$$

$$\sum_{g \in g_c} rs_{gt} \geq RS_{t,c}^{req}, \ \forall t,c,$$

$$\sum_{q=t-UT_g+1}^{t} v_{gq} \leq u_{gt}, \ \forall g, t \geq UT_g,$$

$$\sum_{q=t+1}^{t+DT_g} v_{gq} \leq 1 - u_{gt}, \ \forall g, t \leq |T| - DT_g,$$

$$v_{gt} \geq u_{gt} - u_{g,t-1}, \ \forall g,t,$$

$$f_{kt} - B_k(\theta_{mt} - \theta_{nt}) - M_k(1 - z_{kt}) \leq 0, \ \forall k = (m,n), t,$$

$$-f_{kt} + B_k(\theta_{mt} - \theta_{nt}) - M_k(1 - z_{kt}) \leq 0, \ \forall k = (m,n), t,$$

$$-TC_k z_{kt} \leq f_{kt} \leq TC_k z_{kt}, \ \forall k,t,$$

$$\sum_k (1 - z_{kt}) \leq N, \ \forall t,$$

$$v_{gt}, rs_{gt} \geq 0, \ \forall g,t,$$

$$u_{gt} \in \{0,1\}, \ \forall g,t,$$

$$z_{kt} \in \{0,1\}, \ \forall k,t.$$