Energy-Only Markets with Deferrable Demand

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Motivation and Objectives

- Motivation
  - Integration of renewables $\Rightarrow$ value migrates from energy to capacity
  - Missing money $\Rightarrow$ retirement of flexible units
  - Energy-only market with demand response can reward capacity ...
  - ... but demand function models of *deferrable* demand are inaccurate
- Objectives: How does integration of
  - operating reserve demand curves [Hogan, 2005]
  - deferrable demand

  impact **operations** and **investment**?

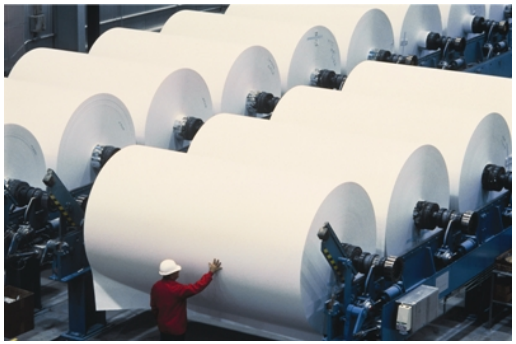
Residential Deferrable Demand

Dryers, dish washers, refrigerators, air conditioning

Commercial Deferrable Demand

Water pumping, ventilation

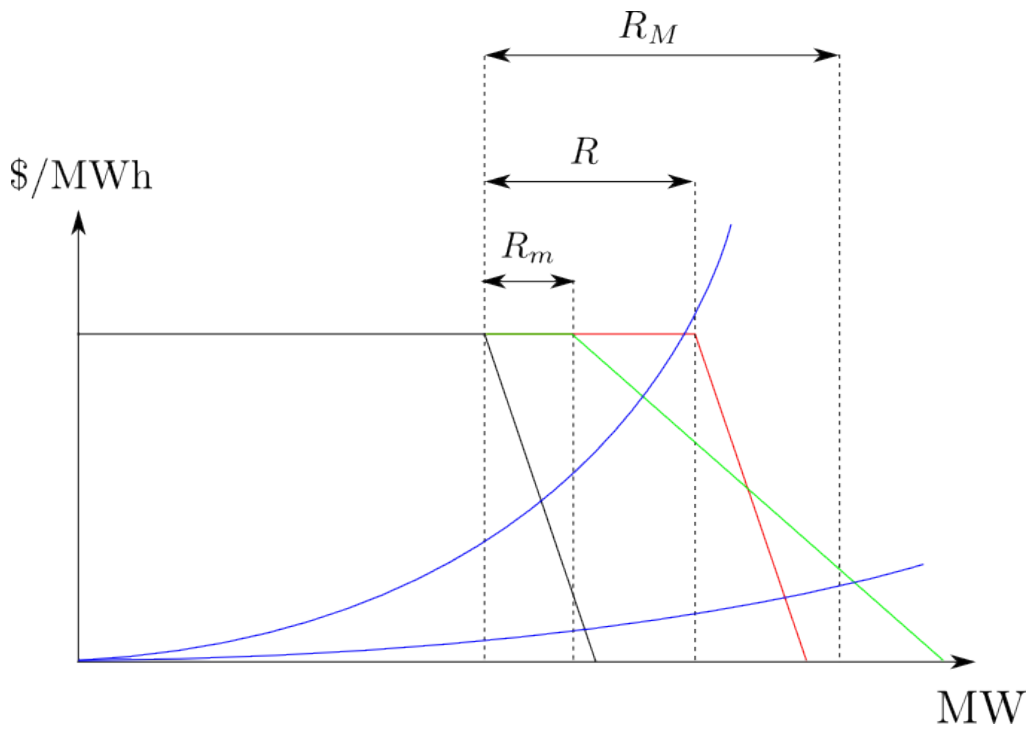
Industrial Deferrable Demand




Pulp paper, water treatment, air liquefaction, cement mills

‘Energy-Only’ Markets [Hogan, 2005]

Idea: reserve demand curve in economic dispatch



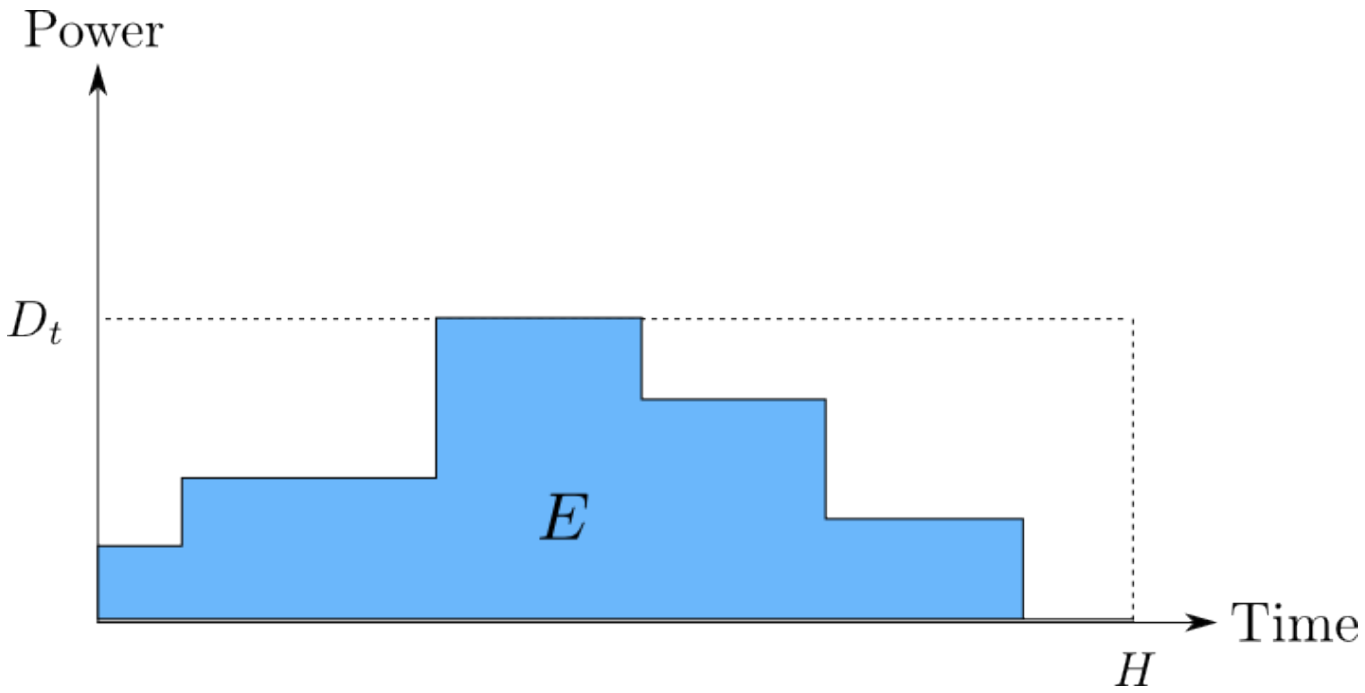
Red: fixed reserve requirement
Green: reserve demand function

Motivation of Proposed Design

- *Short-run efficiency* through co-optimization of reserves and energy
- *Long-run efficiency* through proper scarcity signals
- No *forecasts* required for ICap targets
- *Price spikes* more frequent and smaller
- *Market power* can be mitigated without depressing prices
- Limited *regulatory intervention*: definition of R_m, R_M
  - Below R_m, price = VOLL (involuntary load curtailment)
  - Above R_M, price = 0 (reliability does not improve)
  - Between min and max, capacity has value

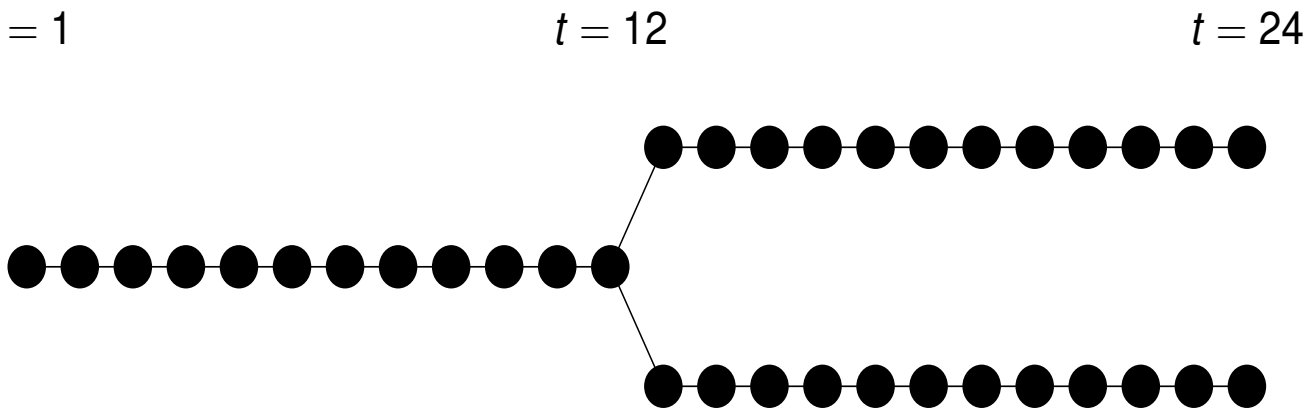
Agents

- Suppliers
  - Conventional and renewable
  - Renewable output is uncertain
  - Income stream: energy + operating reserve markets
- Consumers
  - Non-deferrable consumers (elastic or not)
  - Deferrable consumers
    - Total amount of energy demand E_l within horizon
    - Valuation V_l
    - Consumption rate limit D_l
  - Energy charged as traded commodity
  - Reserve charged as public good (ex-post uplift payments)
- System operator
  - Market clearing and operation
  - Procures reserves on behalf of consumers


Power
D_t
E
Time
H

Uncertainty

- Multistage stochastic program
- Source of uncertainty: renewable supply
- O_t: outcomes in period t
- $A(\omega)$: ancestor of outcome ω



Objective Function

$$\max \sum_{t \in T} \sum_{\omega \in O_t} P_\omega \cdot \int_0^{d_{\omega,t}} VE(x)dx$$

Energy demand function

$$+ \sum_{t \in T} \sum_{\omega \in O_t} P_\omega \cdot \int_0^{r_{\omega,t}} VR(x)dx$$

Reserves demand function

$$- \sum_{l \in DL} \sum_{\omega \in O_H} P_\omega \cdot V_l \cdot x_{l,\omega,H}$$

Cost of unserved deferrable demand

$$- \sum_{g \in G \cup R} \sum_{t \in T} \sum_{\omega \in O_t} P_\omega \cdot \int_0^{p_{g,\omega,t}} MC_g(x)dx$$

Production cost

Constraints

$$p_{g,\omega,t} + rs_{g,\omega,t} \leq C_g, g \in G$$ Max capacity (conventional)

$$p_{g,\omega,t} \leq C_{g,\omega}, g \in R$$ Max capacity (renewable)

$$\sum_{g \in G \cup R} p_{g,\omega,t} = d_{\omega,t} + \sum_{l \in DL} d_{l,\omega,t} + EX_t$$ Energy market clearing

$$\sum_{g \in G} rs_{g,\omega,t} = r_{\omega,t}$$ Reserves market clearing

$$d_{l,\omega,t} \leq D_l$$ Deferrable demand max rate

$$x_{l,\omega,t} = x_{l,A(\omega),t-1} - d_{l,\omega,t}, t \in T - \{1\}$$ Deferrable demand state evolution

$$x_{l,\omega,1} = E_l - d_{l,\omega,1}$$ Deferrable demand state evolution

$$p_{g,\omega,t}, r_{\omega,t}, rs_{g,\omega,t}, d_{\omega,t}, d_{l,\omega,t}, x_{l,\omega,t} \geq 0$$

Focus on Germany

- Demand data: ENTSO-E transparency platform
- Wind and solar power data: EEX Transparency Platform
- Flexible load data: (Gils, 2014)

Germany Fuel Mix

Technology	Capacity (MW)	Min bid (€/MWh)	Max bid (€/MWh)	Average (€/MWh)	*IC* (€/MW-day)
Biomass	4277	0	60.6	30.2	669.6
Coal	24969	14.6	31.6	23.1	388.8
Waste	1329	0	31.0	15.5	902.4
Gas	22236	57.1	95.6	66.3	122.4
Lignite	19847	7.4	13.0	10.2	597.6
Oil	2207	104.6	223.7	164.2	40.8
Other	4534	18.4	21.1	19.8	343.2
Hydro pumped	6759	25.0	125.0	65.0	573.6
Hydro ROR	3677	0	0	0	319.2
Hydro seasonal	1613	25.0	125.0	65.0	319.2
Nuclear	12078	5.9	7.7	6.8	762.2

Source: EEX Transparency Platform

Deferrable Demand Data: Industrial

Type	Sector	Time-varying?	E [TWh/yr]	P [MW]	E [MWh/day]	Flexibility
1	I	No	2.166	260	5934	1.05
2	I	No	4.950	595	13562	1.05
3	I	No	10.940	1315	29974	1.05
4	I	No	0.651	78	1784	1.05
5	I	No	1.473	177	4034	1.05
6	I	No	0.603	72	1651	1.05
7	I	No	0.482	58	1321	1.05
8	I	Yes	4.598	553	12597	1.05
9	I	Yes	4.774	817	13079	1.50
10	I	No	2.556	365	7003	1.25

Deferrable Demand Data: Commercial

Type	Sector	Time-varying?	E [TWh/yr]	P [MW]	E [MWh/day]	Flexibility
11	C	Yes	8.851	1516	24249	1.50
12	C	Yes	1.226	245	3358	1.75
13	C	Yes	1.770	354	4850	1.75
14	C	Yes	17.157	3917	47007	2.00
15	C	Yes	0.136	495	373	31.85
16	C	Yes	2.043	8170	5596	35.04
17	C	Yes	2.723	4190	7461	13.48
18	C	Yes	4.085	933	11192	2.00
19	C	No	4.085	717	11192	1.54

Deferrable Demand Data: Residential

Type	Sector	Time-varying?	E [TWh/yr]	P [MW]	E [MWh/day]	Flexibility
20	R	Yes	9.472	13532	25952	12.51
21	R	Yes	15.741	22487	43126	12.51
22	R	Yes	7.496	25671	20537	30.00
23	R	Yes	4.750	23283	13013	42.94
24	R	Yes	6.888	16557	18870	21.06
25	R	Yes	0.361	1313	990	31.85
26	R	Yes	2.189	8756	5997	35.04
27	R	Yes	14.487	22288	39691	13.48

Classes of flexible loads

1. Pulp production
2. Recycling paper processing
3. Paper machines
4. Calcium carbide production
5. Air liquefaction O2
6. Air liquefaction N2
7. Air liquefaction Ar
8. Cement mills
9. Cooling in food manufacturing
10. Ventilation wo process relevance
11. Cooling, food retailing
12. Cold storages
13. Cooling, hotels and restaurants
14. Commercial ventilation
15. Commercial AC
16. Commercial storage water heater
17. Commercial storage heater
18. Pumps in water supply
19. Waste water treatment
20. Freezer
21. Refrigerator
22. Washing machines
23. Tumble dryers
24. Dish washers
25. Residential AC
26. Residential storage water heater
27. Residential storage heater

- Where is the energy?
  - Residential: 45% of annual flexible energy demand
  - Commercial: 31% of annual flexible energy demand
  - Industrial: 24% of annual flexible energy demand
- Where is the flexibility?
  - Residential: 12.51-42.94%
  - Commercial: 1.5-35.04%
  - Industrial: 1.05-1.5%

Assumptions

- Variable cost:

$$TC(p) = a \cdot p + 0.5 \cdot b \cdot p^2$$

- Two load profiles based on November 6th, 2013
  - Nominal
  - 1.5x
- Renewable supply (scenario tree)
  - Hours 1-12: 5 GW
  - Hours 13-24: 0 GW or 10 GW (equally likely)
- Demand function
  - Inelastic segment (95%): VOLL = 5000 €/MWh
  - Elastic segment (5%): linear, crossing two points
    - Price-quantity from data
    - 0 MW at 10000 €/MWh (VOLL $\simeq$ 5000 €/MWh)

Case Studies Analyzed

1. IE-IR: No deferrable demand, fixed reserve requirement
2. EE-IR: Deferrable demand, fixed reserve requirement
3. IE-ER: No deferrable demand, Hogan reserve pricing
4. EE-ER: Deferrable demand, Hogan reserve pricing

Welfare Results of RT Market

	IE-IR	EE-IR	IE-ER	EE-ER
Welfare	8,314.7	8,315.6	8,314.6	8,315.6
Investment cost	36.5	36.5	36.5	36.5
Generation cost	36.1	35.2	36.1	35.2
Energy Payments	79.0	75.6	104.5	75.6
Reserve payments	0	0	2.1	0
Generation profits	6.4	4.0	34.0	4.0
Non-def benefit	6,515.3	6,515.3	6,515.2	6,515.3
Deferrable benefit	1,872.0	1,872.0	1,872.0	1,872.0
Load profit	8,308.3	8,311.7	8,280.6	8,311.7

Results in million €

Energy and Reserve Price Statistics of RT Market

	IE-IR	EE-IR	IE-ER	EE-ER
Average E	55.9	52.5	77.6	52.5
Min E	22.8	25.5	22.8	25.5
Max E	93.3	79.3	2178.3	79.3
St. dev. E	21.4	22.1	216.6	22.1
Average R	n/a	n/a	21.7	0
Min R	n/a	n/a	0	0
Max R	n/a	n/a	2085.9	0
St. dev. R	n/a	n/a	211.8	0

Results in €/MWh

Conclusions

- EE-IR and EE-ER are identical. Due to deferrable demand, there is an oversupply of operating reserve
- Generation cost decrease resulting from deferrable demand: 2.57-2.6%
- Cost increase resulting from operating reserve demand curve: 0.3%
- Generation profits peak in IE-ER
- Load profits drop in case IE-ER

Perspectives

Impact of Hogan energy-only market model in Belgian market

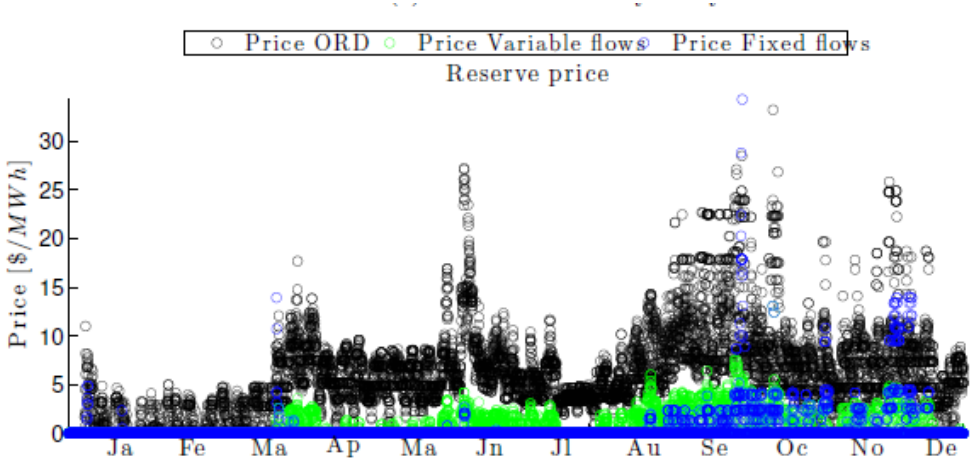


FIGURE 7 – Reserve price