Resource Adequacy

Quantitative Energy Economics

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Capacity Expansion Planning

Long-term planning problem that determines mix of generation technologies that minimize total cost of *expanding* and *operating* a system

In its simplest form:

- Two-stage optimization
  - First stage: invest in each technology
  - Second stage: operate technologies in order to satisfy demand
- Ignores demand response

Load Versus Demand

Load: amount of power that would be consumed if energy were supplied at zero price

Demand: consumption at a given price

- Equal to supply
- Less than or equal to load

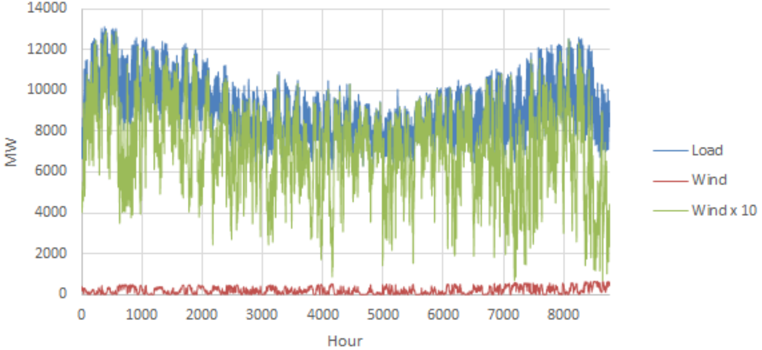
Example: Load Versus Demand

Consider a system with one generator (100 MW) and demand function

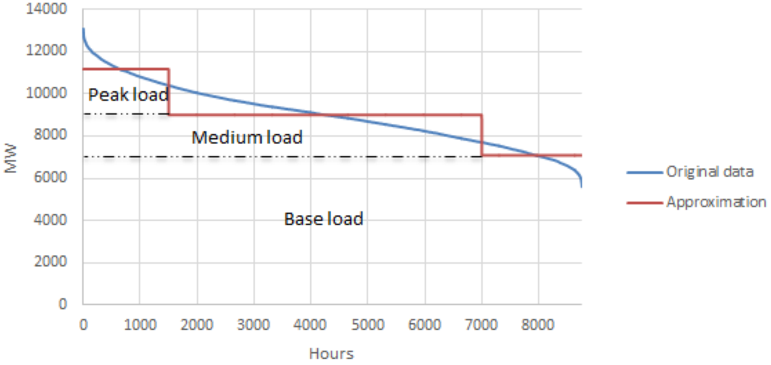
$$D(v) = 110 - 5v$$

- Load: 110 MW
- Demand cannot exceed 100 MW

Load and Wind in Belgium, 2013

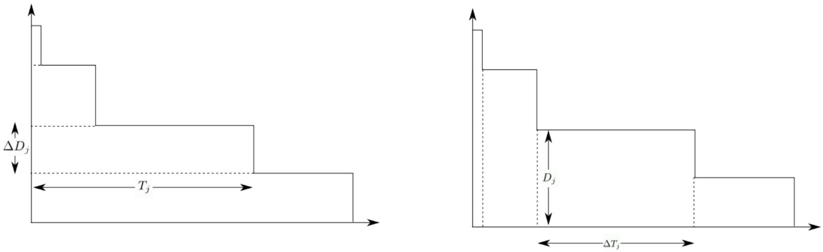


Load Duration Curve



Load duration curve is obtained by sorting load time series in descending order

Figure: Left: a horizontal partition of the load duration curve into load slices. Right: a vertical partition of the load duration curve into time slices.



Capacity Expansion Planning Model

Two-stage deterministic capacity expansion without flexible demand:

$$\min \sum_{g \in G} I_g x_g + \sum_{j=1}^{m} \Delta T_j \sum_{g \in G} C_g p_{gj}$$

$$\sum_{g \in G} p_{gj} = D_j$$

$$p_{gj} \leq x_g$$

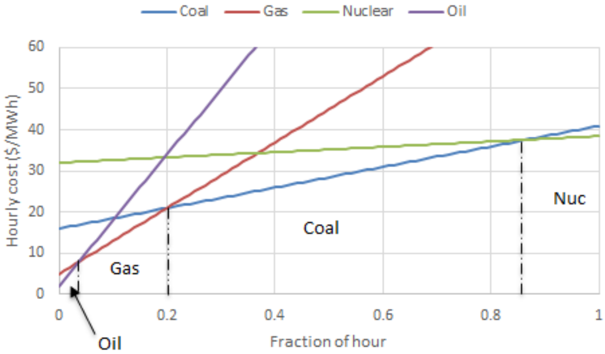
$$p, x \geq 0$$

- ΔT_j: duration of vertical slice j
- D_j: demand of vertical slice j (MW)
- I_g: investment cost of technology g (\$/MWh)
- C_g: marginal operating cost of technology g (\$/MWh)
- x_g: investment in technology g (MW)
- p_{gj}: energy from technology g supplied to slice j (MWh)

Remarks

- If $I_1 \leq I_2 \leq \ldots \leq I_n$ then $C_1 \geq C_2 \geq \ldots \geq C_n$
- Model can be enriched to include
  - transmission constraints
  - availability factors of technologies
  - multiple time stages
  - discount rates
  - uncertainty

Screening Curves



Screening curve: Total hourly cost as a function of the fraction of time that a technology is producing

Investment Cost

Fixed/investment cost: cost that is independent of output

- **Overnight cost** ($/kW): cost that needs to be paid upfront per kW of investment
- **Annualized fixed cost** ($/kWy): cost that needs to be paid per year per kW of investment
- **Hourly fixed cost** ($/MWh): cost that needs to be paid per hour per MW of investment

Conversion of Investment Cost

Denote

- T (years): investment lifetime
- r: interest rate

Annualized fixed cost FC ($/kWy) given *annual discounting*:

$$FC = \frac{r \cdot OC}{1 - 1/(1+r)^T}$$

Annualized fixed cost FC ($/kWy) given *continuous discounting*:

$$FC = \frac{r \cdot OC}{1 - e^{-rT}}$$

Hourly fixed cost ($/MWh): Divide annualized fixed cost by 8.76 (why 8.76?)

Example

- Gas turbine lifetime: 25 years
- Coal generator lifetime: 45 years
- Continuous discounting with interest rate $r = 12\%$

	OC (\$/kW)	FC (\$/kWy)	FC (\$/MWh)
Gas turbine	400	50.5	5.8
Coal	1200	144.7	16.5

Capacity Expansion Planning with Demand Response

Demand function j approximated by block bids (V_{lj}, D_{lj}): D_{lj} MW at V_{lj} \$/MWh

$$\max \sum_{j=1}^{m} \Delta T_j (\sum_{l \in L} V_{lj} d_{lj} - \sum_{g \in G} C_g p_{gj}) - \sum_{g \in G} I_g x_g$$

$$\sum_{l \in L} d_{lj} - \sum_{g \in G} p_{gj} = 0, (\rho_j)$$

$$p_{gj} - x_g \leq 0, (\mu_{gj})$$

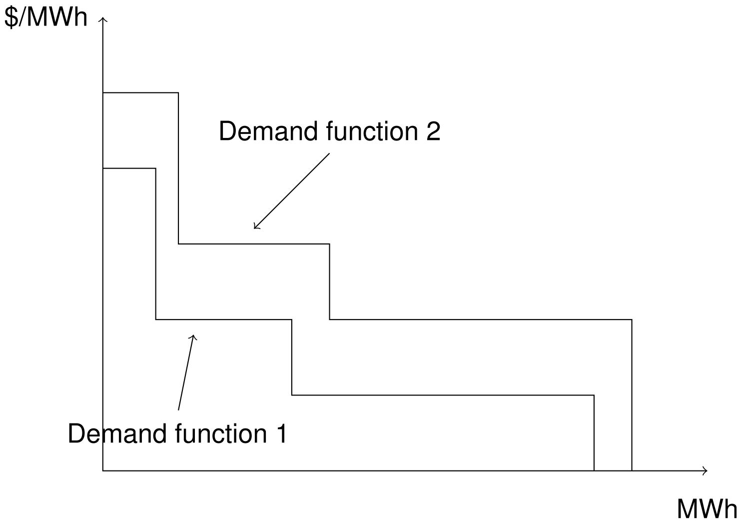
$$d_{lj} \leq D_{lj}, (\nu_{lj})$$

$$p, x, d \geq 0$$

Alternative interpretation: two-stage stochastic capacity expansion planning problem with demand uncertainty

- interpret j as scenario indices
- interpret ΔT_j as probabilities

Graphical Illustration of Demand Functions



KKT Conditions of the Capacity Expansion Planning Problem

$$
\begin{aligned}
\sum_{l \in L} d_{lj} \quad &- \quad \sum_{g \in G} p_{gj} = 0 \\
0 \leq \mu_{gj} \quad &\perp \quad x_g - p_{gj} \geq 0 \\
0 \leq \nu_{lj} \quad &\perp \quad D_{lj} - d_{lj} \geq 0 \\
0 \leq p_{gj} \quad &\perp \quad \Delta T_j C_g + \mu_{gj} - \rho_j \geq 0 \\
0 \leq d_{lj} \quad &\perp \quad -\Delta T_j V_{lj} + \nu_{lj} + \rho_j \geq 0 \\
0 \leq x_g \quad &\perp \quad I_g - \sum_{j=1}^{m} \mu_{gj} \geq 0
\end{aligned}
$$

Consumption Criterion

Three cases:

- $0 < d_{lj} < D_{lj}$: in this case $V_{lj} = \rho_j / \Delta T_j$
- $d_{lj} = 0$: in this case $V_{lj} \leq \rho_j / \Delta T_j$
- $d_{lj} = D_{lj}$: in this case $V_{lj} \geq \rho_j / \Delta T_j$

Conclusion: For each j there is a threshold $\rho_j / \Delta T_j$ of valuation for determining consumption

Production Criterion

Three cases for generators with $x_g > 0$:

- $0 < p_{gj} < x_g$: in this case $C_g = \rho_j / \Delta T_j$
- $p_{gj} = 0$: in this case $C_g \geq \rho_j / \Delta T_j$
- $p_{gj} = x_g$: in this case $C_g \leq \rho_j / \Delta T_j$

Conclusion: For each j there is a threshold $\rho_j / \Delta T_j$ of marginal cost for determining production

Investment Criterion

Two cases:

- $x_g = 0$: in this case $I_g \geq \sum_{j=1}^{m} \mu_{gj}$
- $x_g > 0$: in this case $I_g = \sum_{j=1}^{m} \mu_{gj}$

Conclusion: There is a threshold $\sum_{j=1}^{m} \mu_{gj}$ of investment cost for determining investment

Utilization of Investment

Suppose $p_{gj} < x_j$ for all $j \in \{1, \ldots, m\}$ for some technology g

- $\mu_{gj} = 0$ for all j
- $I_g = \sum_{j=1}^{m} \mu_{gj} = 0$
- If $I_g > 0$ then $p_{gj} < x_j$ for all $j \in \{1, \ldots, m\}$ cannot hold

Conclusion: We operate investments to their full capacity ($p_{gj} = x_g$ for some j)

An Example of Expansion Planning

	I_g (\$/MWh)	C_g (\$/MWh)
Gas turbine	5.8	30
Coal	16.5	18

Three demand functions

- Type 1: $\Delta T_1 = 0.5$, $D_1 = 4000$ MW at $V_1 =$1000 \$/MWh
- Type 2: $\Delta T_2 = 0.495$, $D_2 = 7975$ MW at $V_2 =$1000 \$/MWh
- Type 3: $\Delta T_3 = 0.005$, $D_3 = 8000$ MW at $V_3 =$1000 \$/MWh

Optimal solution:

- $x_{coal} = 4000$ MW, $x_{gas} = 3975$ MW
- $\rho_1 = 13.7$ \$/MWh, $\rho_2 = 15.8$ \$/MWh, $\rho_3 = 5$ \$/MWh

Checking the Results

- Utilization of investment: entire capacity used for serving $j = 2$
- Consumption criterion
  - $1000 = V_1 > \rho_1/\Delta_1 = 13.7/0.5 = 27.4$, full service for $j = 1$
  - $1000 = V_2 > \rho_2/\Delta_2 = 15.8/0.495 = 31.9$, full service for $j = 2$
  - $1000 = V_3 \leq \rho_3/\Delta_3 = 5/0.005 = 1000$, no service for $j = 3$
- Production criterion
  - $18 = C_{coal} < \rho_j/\Delta_j$ for $j = 1, 2$, coal serves $j = 1$ and 2
  - $30 = C_{gas} < \rho_2/\Delta_2$, gas only serves $j = 2$

Uncertainty and Multiple Time Periods

Why multiple stages?

- Long-term evolution of equipment costs (e.g. natural gas prices)
- Long-term evolution of load duration curve
  - Industrial activity
  - Energy savings
  - Rate policy
- New technologies (e.g. solar)
- Retirement of current equipment (e.g. nuclear in Germany)

Why uncertainty? For the same reasons.

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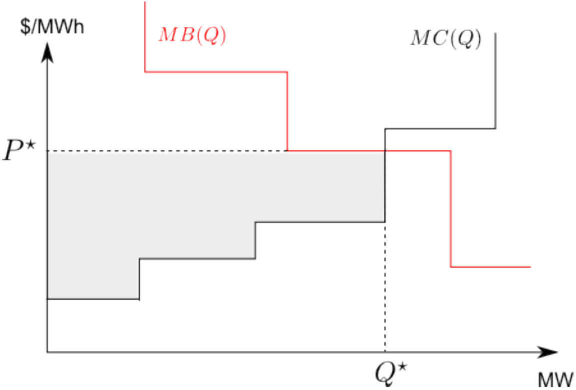
Energy-Only Markets

Energy-only markets: energy markets that rely *exclusively* on energy price spikes in order to finance capital costs of investment in generation through **scarcity rents**

Scarcity rents: energy market revenue minus variable costs (this does not include startup and minimum load costs)

Graphical Illustration of Scarcity Rent



- $MC(\cdot)$: system marginal cost curve
- $MB(\cdot)$: system marginal benefit
- $P^\star$ [$Q^\star$]: market clearing price [quantity]
- Shaded gray area: scarcity rent

Equilibrium Model of Energy-Only Market

Agents:

- Electricity producers
- Electricity consumers

Commodities (scarce resources):

- Energy
- Capacity

Markets:

- Energy market (different price ρ_j for each time slice j)
- Note: there is *no* market for capacity

Producer Quantity Adjustment

$$\max \sum_{j=1}^{m} (\rho_j - C_g) \cdot \Delta_j \cdot p_{gj} - I_g \cdot x_g$$

$$(\mu_{gj}): \quad p_{gj} - x_g \leq 0$$

$$p_{gj} \geq 0$$

KKT conditions:

$$0 \leq p_{gj} \quad \perp \quad \mu_{gj} - (\rho_j - C_g)\Delta_j \geq 0$$

$$0 \leq x_g \quad \perp \quad I_g - \sum_{j=1}^{m} \mu_{gj} \geq 0$$

$$0 \leq \mu_{gj} \quad \perp \quad x_g - p_{gj} \geq 0$$

Consumer Quantity Adjustment

$$\begin{aligned} & \max(V_{lj} - \rho_j)d_{lj} \\ (\nu_{lj}): \quad & d_{lj} - D_{lj} \leq 0 \\ & d_{lj} \geq 0 \end{aligned}$$

KKT conditions:

$$0 \leq d_{lj} \quad \perp \quad \nu_{lj} + \rho_j - V_{lj} \geq 0$$

$$0 \leq \nu_{lj} \quad \perp \quad D_{lj} - d_{lj} \geq 0$$

Price Adjustment

Market clearing condition for energy market:

$$0 \leq \rho_j \perp \sum_{g \in G} p_{gj} - \sum_{l \in L} d_{lj} \geq 0$$

Observations

- Markets are efficient: KKT conditions of competitive market equilibrium $\Leftrightarrow$ KKT conditions of centralized expansion planning
- Equivalence holds if we account for transmission constraints and demand-side uncertainty
- From the KKT conditions, if $p_{gj} > 0$ then

$$\mu_{gj} = (\rho_j - C_g)\Delta_j$$

  This is the **scarcity rent** we defined earlier
- Restatement of investment criterion: investment will only take place if scarcity rent can cover investment cost, competition will push scarcity rents to exactly equal investment cost:

$$0 \leq x_g \perp I_g - \sum_{j=1}^{m} \mu_{gj} \geq 0$$

The Two-Technology System Revisited

	I_g (\$/MWh)	C_g (\$/MWh)
Gas turbine	5.8	30
Coal	16.5	18

Three demand functions

- Function 1: $\Delta T_1 = 0.5$, $D_1 = 4000$ MW at $V_1 =$1000 \$/MWh
- Function 2: $\Delta T_2 = 0.495$, $D_2 = 7975$ MW at $V_2 =$1000 \$/MWh
- Function 3: $\Delta T_3 = 0.005$, $D_3 = 8000$ MW at $V_3 =$1000 \$/MWh

Optimal solution:

- $x_{coal} = 4000$ MW, $x_{gas} = 3975$ MW
- $\rho_1 = 27.4$ \$/MWh, $\rho_2 = 31.92$ \$/MWh, $\rho_3 = 1000$ \$/MWh

Scarcity Rents

- Gas generator: majority of scarcity rents from demand function 3
  - $\mu_{gas,2} = (31.92 - 30) \cdot 0.495 = 0.95$ \$/MWh
  - $\mu_{gas,3} = (1000 - 30) \cdot 0.005 = 4.85$ \$/MWh
  - $I_{gas} = \mu_{gas,2} + \mu_{gas,3} = 5.8$ \$/MWh
- Coal generator: earns scarcity rents from all demand functions
  - $\mu_{coal,1} = (27.4 - 18) \cdot 0.5 = 4.7$ \$/MWh
  - $\mu_{coal,2} = (31.92 - 18) \cdot 0.495 = 6.89$ \$/MWh
  - $\mu_{coal,3} = (1000 - 18) \cdot 0.005 = 4.91$ \$/MWh
  - $I_{coal} = \mu_{coal,1} + \mu_{coal,2} + \mu_{coal,3} = 16.5$ \$/MWh

Observations:

- Scarcity rents are earned in *all* demand levels, not only when demand is curtailed
- Scarcity rents are very risky for gas because it is difficult to exactly forecast duration of demand function 3

Energy-Only Markets in Practice

Advantage: results in optimal investment and operation of the system in case of *perfect competition*

Disadvantages in practice:

- Low elasticity of demand $\Rightarrow$ price volatility $\Rightarrow$ uncertain scarcity rents $\Rightarrow$ investment is risky
- Demand curtailment cannot be enforced in real time $\Rightarrow$ markets will not clear for some hours $\Rightarrow$ regulator - not market - has to set a market price for those hours

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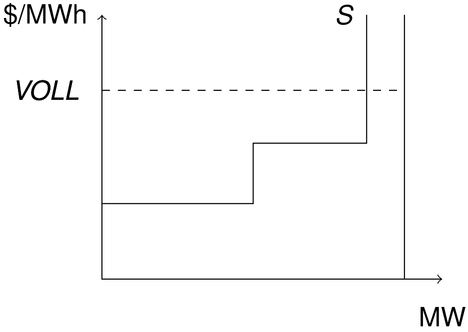
VOLL Pricing

- Efficiency dictates that load *should not* be satisfied at all times
- What happens to the real-time market at these times?

Value of lost load pricing (VOLL pricing): system operator buys power on behalf of loads at regulated price *VOLL*

- Inelastic demand is curtailed randomly
- *VOLL* is used as a real-time price
  - Used for settling forward (including day-ahead market) contracts
  - Used for paying real-time production, charging real-time demand

Graphical Interpretation of *VOLL* Pricing



Dashed line: demand curve if all load had same valuation *VOLL*

- Real-time price would be *VOLL*
- Random rationing of any load would be efficient

Equilibrium Analysis

- Market agents: system operator, generators, *not* inelastic consumers
- Markets: one energy market for each mode of demand
- Generator quantity adjustment

$$\max \sum_{j=1}^{m} (\rho_j - C_g) \cdot \Delta_j \cdot p_{gj} - I_g \cdot x_g$$

$$p_{gj} - x_g \leq 0, (\mu_{gj})$$

$$p_{gj}, x_g \geq 0$$

- Price adjustment: energy market clearing

$$0 \leq \rho_j \perp \sum_{g \in G} p_{gj} + l_j - \sum_{l \in L} D_{lj} \geq 0$$

- VOLL mechanism

$$0 \leq l_j \perp VOLL - \rho_j \geq 0$$

Features of VOLL pricing

- Advantage: efficient equilibrium
- Disadvantages
  - High annual variance of load curtailment $\Rightarrow$ high variance of scarcity rent $\Rightarrow$ high investment risk
  - Estimation of *VOLL* is difficult and non-transparent
  - Market power

Scarcity and High Prices

High prices indicate scarcity and need for investment

In systems with scarce capacity and inelastic demand, prices are highly volatile

Fixed reserve requirements $\Rightarrow$ inelastic demand for reserve

Motivation of operating reserve demand curves: elastic demand for reserve $\Rightarrow$ less volatile prices

Example

- D MW of inelastic demand
- Marginal benefit of inelastic demand: 1000 \$/MWh
- 100 MW of elastic demand
- Marginal benefit of elastic demand:

$$MB_L(x) = \begin{cases} 1000 \text{ \$/MWh}, \\ 0 \text{ MW} \leq x \leq D \text{ MW} \\ 1000 - 10 \cdot (x - D) \text{ \$/MWh}, \\ D \text{ MW} \leq x \leq D + 100 \text{ MW} \end{cases}$$

- Installed capacity: 10000 MW
- Aggregate marginal cost:

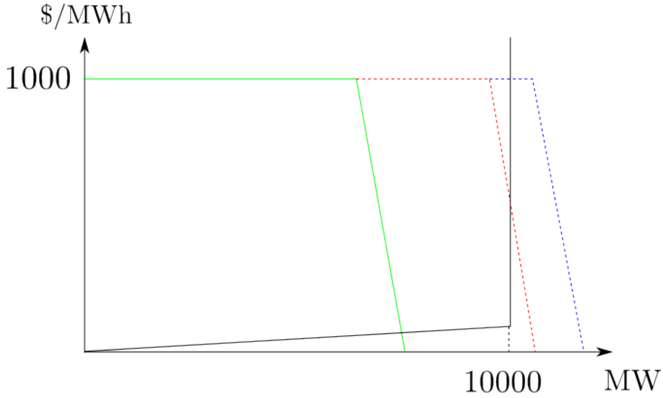
$$MC_G(x) = 0.015x \text{ \$/MWh}$$

- Fixed reserve requirement: $R = 1000$ MW

Energy price (derive this):

$$\lambda^\star = \begin{cases} 0.015\frac{1000+10(D+R)}{10.015} \text{ \$/MWh}, \\ 0 \text{ MW} \leq D+R \leq 9915 \text{ MW} \\ 1000 - 10 \cdot (10000 - D - R) \text{ \$/MWh}, \\ 9915 \text{ MW} < D+R \leq 10000 \text{ MW} \\ 1000 \text{ \$/MWh}, \\ D+R > 10000 \text{ MW} \end{cases}$$

How many MW of inelastic demand does it take for price to jump from 150 \$/MWh to 1000 \$/MWh?



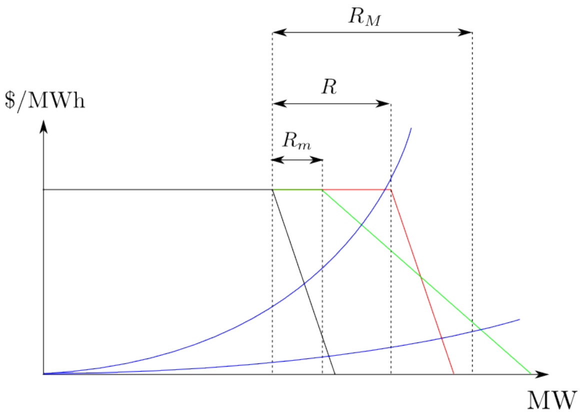
Demand function for power + reserve:

- Green: $D + R \leq 9915$ MW
- Red: $9915 \text{ MW} \leq D + R \leq 10000$ MW
- Blue: $D + R > 10000$ MW

Operating Reserve Demand Curves

Suppose:

- system operator willing to curtail loads involuntarily when reserves $\leq R_m$
- reliability does not improve when reserves $\geq R_M$



- Black curve: demand function for power
- *R*: fixed reserve requirement
- Red curve: demand function for power and reserves, model (*EDR*)
- R_m, R_M: parameters of reserve demand function
- Green curve: demand function for power and reserves, model (*ORDC*)
- Blue curves: supply functions

Uniform Pricing with Reserve Demand Curves

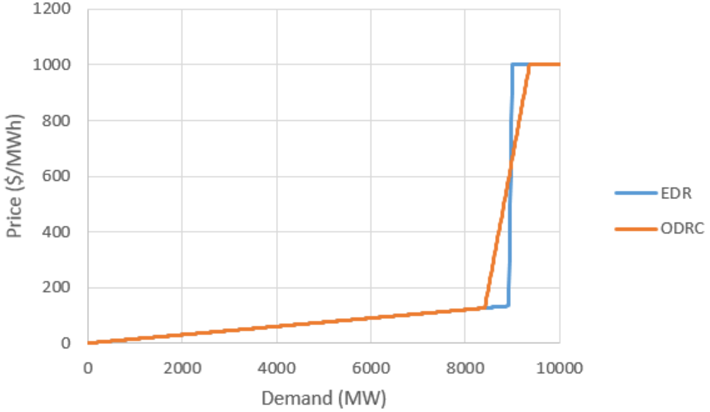
A uniform pricing auction for reserves based on an operating reserve demand function is conducted as follows:

- Suppliers submit increasing bids for power, consumers submit decreasing bids for power. The system operator submits decreasing bids for reserve.
- The market operator solves (*ORDC*) and announces λ as the uniform price for power, μ as the uniform price for reserve.

$$
\begin{aligned}
(ORDC): \quad & \max \sum_{l \in L} \int_0^{d_l} MB_l(x)dx + \int_0^{r} MR(x)dx \\
& - \sum_{g \in G} \int_0^{p_g} MC_g(x)dx \\
(\lambda): \quad & \sum_{l \in L} d_l - \sum_{g \in G} p_g = 0 \\
(\mu): \quad & r - \sum_{g \in G} r_g = 0 \\
& r_g \leq R_g \\
& p_g + r_g \leq P_g \\
& p_g, d_l, r_g \geq 0
\end{aligned}
$$

$MR(\cdot)$: marginal benefit for reserve

Example



- Orange curve: (*EDR*) with $R = 1000$ MW
- Blue curve: (*ORDC*) with $R_m = 500$ MW, $R_M = 1500$ MW