# Course notes for EE394V Restructured Electricity Markets: Locational Marginal Pricing

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# 7
# Economic decision-making

1. Construction and operation,
2. Central planning versus markets,
3. Goals of decision-making,
4. Central planning,
5. Markets,
6. Market idealizations,
7. Competition in electricity,
8. Ideal central planning,
9. Bilateral contracts versus auctions,
10. Homework exercise.

# 7.1 Economic decision-making: Two aspects in electricity industry.

1. Investment/Construction:
   - When, what type, and where to build generators, transmission lines, distribution lines, substations.
2. Scheduling/Operations:
   - Which generators to operate, given technical limitations on their operation and on the operation of the transmission system.

- Our main focus this semester is on scheduling/operations, but we also need to keep investment/construction in mind.

# 7.2 Economic decision-making: Two extremes of mechanisms.

1. Central planning:
   - Central decision-maker makes all decisions,
   - Historically the dominant approach for essentially all aspects of electric power: generation, transmission, distribution, system operation, retail sales,
2. Markets:
   - Individual participants make decisions in reaction to prices.
   - Now in place in many countries for generation and retail functions.

# 7.3 Goals of decision-making.

- What is a desirable outcome of economic decision process from a public policy perspective?
  - Maximize surplus (benefits of consumption minus costs of production).
- Other outcomes, such as distributional equity, may also be desired:
  - We will focus on maximizing surplus since it can be the natural result of market action,
  - Typically, achieving other desired outcomes requires explicit actions, such as taxation.

# 7.4 Central planning

- Central planning *could* maximize surplus:
  - would require all the relevant information to be known by the central planner,
  - assuming that the planner is motivated to achieve surplus maximization.

# 7.5 Markets

- Can (ideally) also maximize surplus through markets in the absence of a single entity knowing everything:
  - Firms presumably want to maximize (operating) profits, and
  - Consumers presumably want to maximize the benefits of consumption minus payment,
  - Under appropriate circumstances, these motivations result in surplus maximization:
    - Circumstances are not satisfied exactly in practice, but ideal case provides useful benchmark.

# Markets

- Consider two optimization problems:

1. Maximizing surplus (imagine central planner solving this problem):
   - Solution of optimization problem at each time provides Lagrange multiplier on constraint requiring supply to equal demand,
   - Under suitable assumptions for validity of sensitivity analysis, Lagrange multiplier indicates marginal cost of serving additional demand, and marginal savings if demand decreases, the **marginal surplus**,
2. Operating profit maximization of a firm, given a price for sale of its production.

# Markets

- Key observation is that if prices faced by firms are the same as Lagrange multipliers in surplus maximization problem then firm behaves consistently with surplus maximization:
  - As we have seen in several examples.
- If firms face the "right" prices then profit-maximization is consistent with maximizing surplus:
  - Prices "support" efficient behavior by the firms.
- Similar observation applies to demand-side.

# 7.6 Market idealizations

- Various assumptions are needed in order for the prices in the market to be "right:"
  - There must be markets for every possible commodity traded, including markets for "bads" such as pollution, so that there are no "externalities,"
  - There must be no economies of scale,
  - There must be sufficient competition between participants,
  - There must be a process that adjusts/determines the market prices.

# 7.6.1 Externalities

- When there are costs imposed by the action of one participant on others, we generally cannot rely on the "market" to provide the right prices:
  - Implies role of government to provide regulation or taxation to internalize imposed costs,
  - Classic examples in electricity are regulation of $SO_x$ and $NO_x$,
  - Topical example in electricity is regulation of $CO_2$ using cap and trade or carbon tax.

# 7.6.2 Economies of scale

- Cheaper per unit installed capacity for larger capacity or cheaper per unit production for larger production.
- Electricity industry capacity economies of scale traditionally thought to be extreme:
  - "natural monopoly," where a single producer was the cheapest way to operate industry,
  - No scope for competition and market if there is only a single producer!
  - Single company is regulated by government.

# Economies of scale

- More recently, competition in generation sector perceived as viable:
  - Particularly for combined cycle gas turbines, the minimum capacity necessary to reap economies of scale is small compared to annual average demand growth in a large interconnection,
  - Minimum capacity to reap economies of scale in wind turbine is around a few MW.
  - So several competitors can each be building new capacity needed for growth at the scale necessary to reap scale economies.

# 7.6.3 Sufficient competition

- If industry is large enough that there could be several firms, each large enough to reap economies of scale but small enough to be a small fraction of total industry, then competition is likely to result in better outcomes than central planning:
  - Competition between firms will keep current prices low and encourage technological innovation to keep future prices low.
  - In contrast, monopolies typically do not innovate strongly.

# 7.6.4 Price adjustment

- In many markets, including the market for apartments, we can assume that self-interested behavior of market participants will result in price adjustment:
  - If price is above market clearing price, landlords will want to adjust prices up.
- We will see that in the context of short-term markets for electricity, we need to explicitly set up a "mechanism" to determine prices from offers.

# 7.7 Competition in electricity

- The move to a competitive generation sector has taken place in many countries and many states of the US.
- Examples of wholesale restructuring:
  - Chile, Norway, United Kingdom, Sweden, Finland, Denmark, New Zealand, Australia,
  - California, PJM, New England, New York, ERCOT, Midwest.
- Retail competition also in place in some jurisdictions, including:
  - United Kingdom, Australia,
  - ERCOT, several Northeastern US states.

# 7.8 Ideal central planning

- Our goal is to understand in more detail how markets might achieve the same outcome as ideal central planning.
- We first need to understand ideal central planning for construction and operations.
- First simplify to case where at any given time demand is fixed:
  - Will expand analysis to include price responsive demand with willingness-to-pay,
  - Price responsive demand is important to inform market about need for capacity.

# Ideal central planning

- Our focus in rest of course will mostly be on operating existing generation.
- However, here we will consider both operations and construction:
  - Incentives for building generation capacity are an essential role for electricity markets!
  - Cannot *just* consider operations.
- We will first consider conditions characterizing the optimal amount of each type of capacity and how to operate it.

# 7.8.1 Assumptions

- We will ignore:
  - "lumpiness" of actual generation expansion (and operation),
  - the fact that generation investments are typically "sunk,"
  - uncertainties in demand, fuel costs, investment costs, and in the availability of generators, and
  - the effects of the transmission system.

# Assumptions

- Assume that capacity of generator of type *k* can be "rented" at cost $r_k$ in \$/MW.year:
  - This is the annual capital carrying cost of owning the generator, per unit capacity,
  - Includes any "profit" to the investor.
- Assume that the marginal operating cost of generators of type *k* is $c_k$ in \$/MWh:
  - Ignore minimum and maximum capacity of generator, variation in marginal costs, and assume that generators are available in "infinitesimal" slices of capacity.

# 7.8.2 Generator total costs

- Suppose that some generators of type $k$ were operated at full output for $t_k$ hours per year and were out-of-service the rest of the year:
  - The annual total cost per unit capacity for both capital and operating costs would be $r_k + t_k c_k$,
  - Increasing linear function of $t_k$.
- Note that if one type of generator $k$ "dominated" another type $l$, in that, for all $t$, we had $r_k + t c_k < r_l + t c_l$, then we would never build any generators of type $l$.

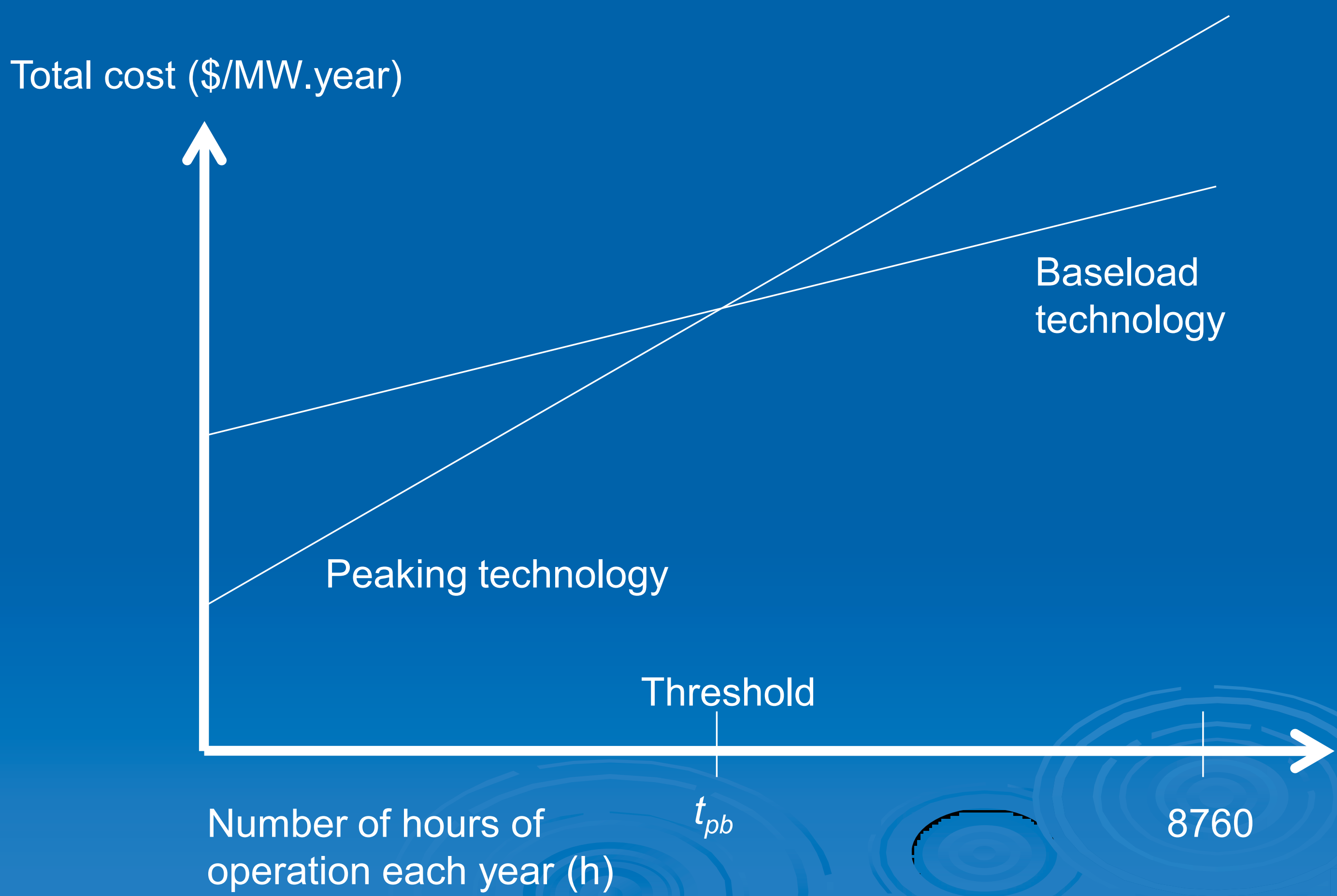
# Generator total costs

- Typically, there are several types of capacity that are not dominated by any other type:
  - The optimal choice of type to build will depend on the time of operation.
- We will consider just two types of capacity:
  - Baseload, *b*, and
  - Peaker, *p*,
  - Analysis also works for more than two types.

# Generator total costs

- Basic insight:
  - Low marginal cost, high capital cost technologies ("baseload") are cheapest when used for more hours, whereas
  - High marginal cost, low capital cost technologies ("peaking") are cheapest when used for fewer hours.
  - Threshold occurs for annual operating time when values of $r_k + t_k\, c_k$ are equal.
  - For baseload and peaker, threshold $t_{pb}$ satisfies: $r_p + t_{pb}\, c_p = r_b + t_{pb}\, c_b$ .

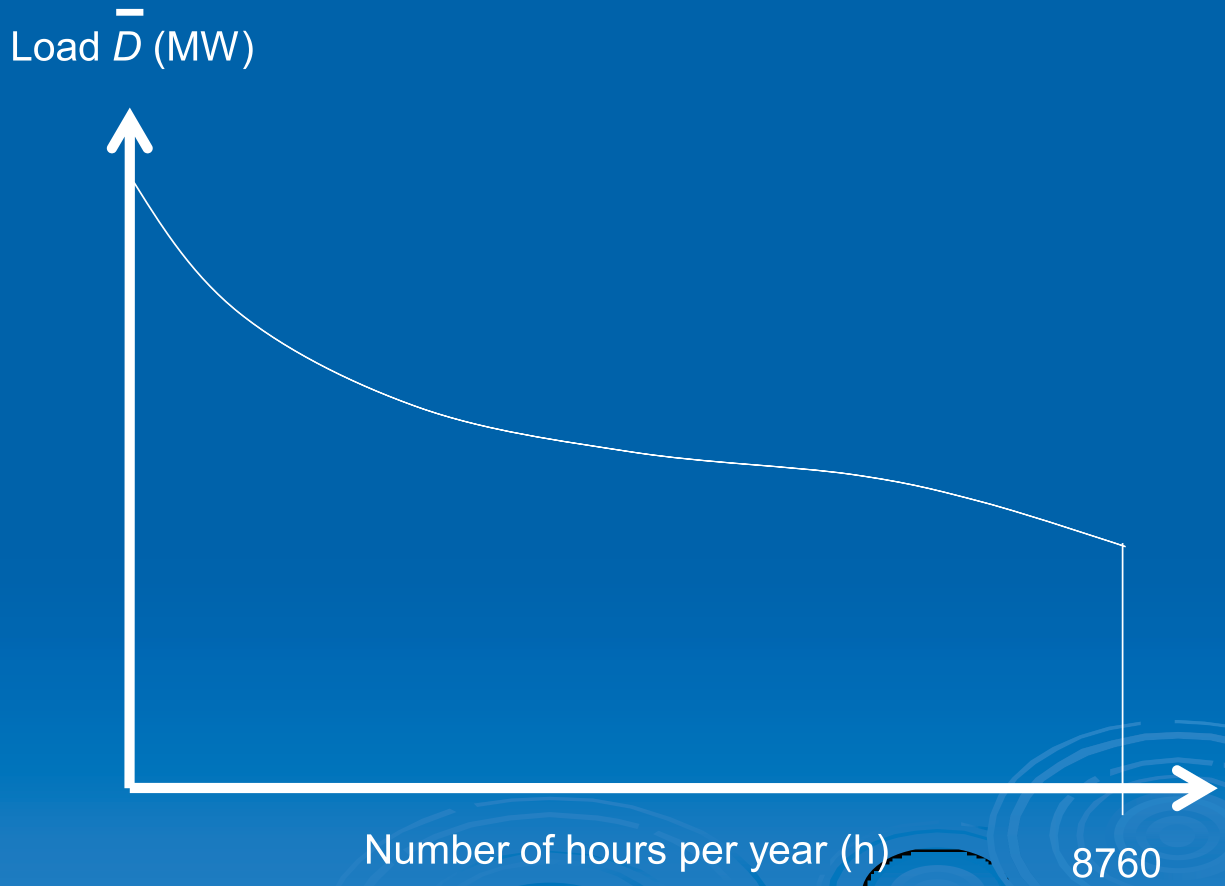
# Generator total costs



# 7.8.3 Load-duration curve

- Consider the demand over a given year of 8760 hours.
- For any particular demand level, we can evaluate the number of hours that the demand exceeds that level:
  - Load-duration curve,
  - Same information as a cumulative distribution function for demand.

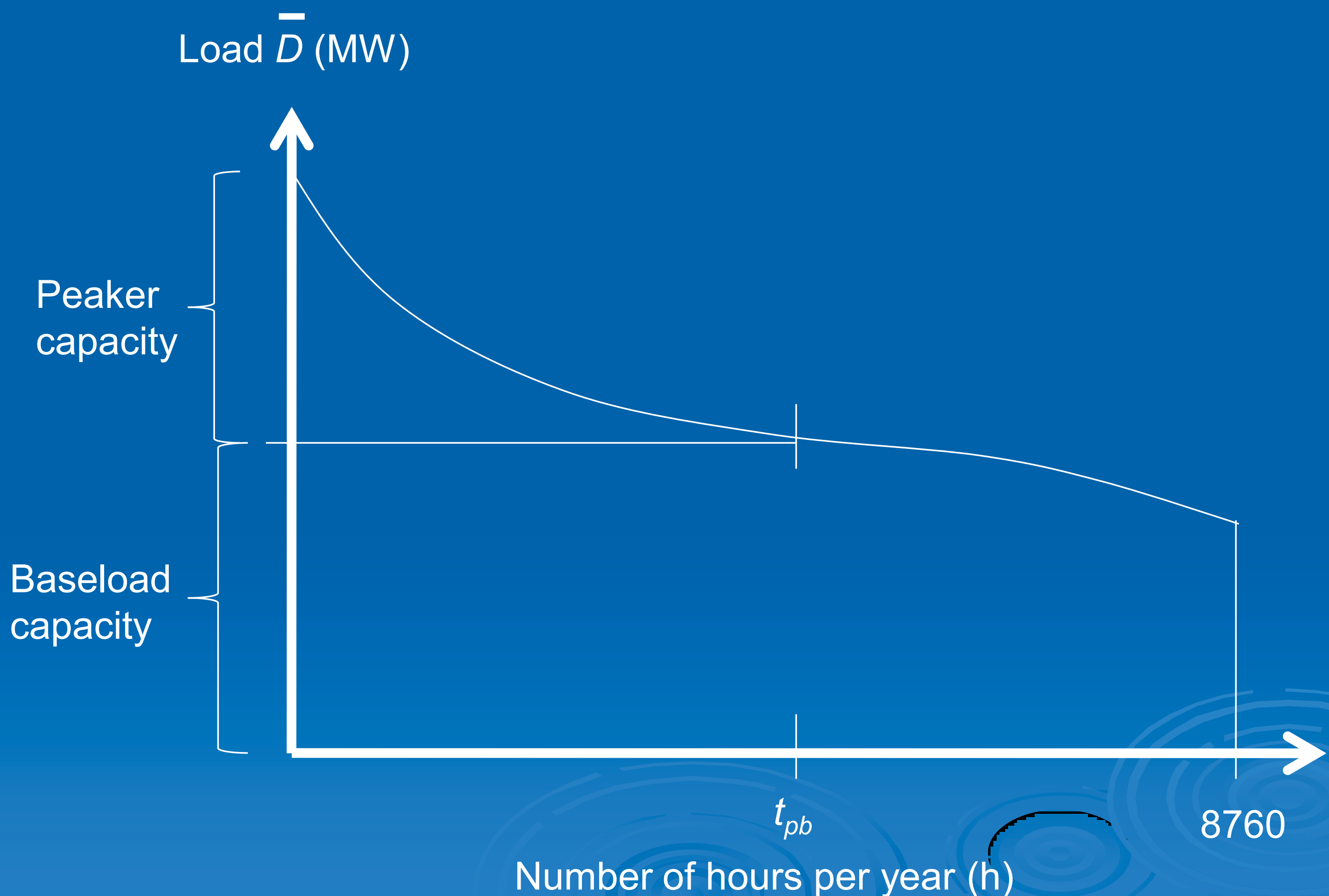
# Load-duration curve



# Load-duration curve

- Divide up the load-duration curve into horizontal infinitesimal slices:
  - Each horizontal slice has a particular duration,
  - Each slice can be most economically served by the type of capacity that is cheapest for the corresponding duration:
    - Baseload cheapest for capacity serving durations longer than threshold $t_{pb}$,
    - Peaking cheapest for capacity serving durations shorter than threshold $t_{pb}$.

# Load-duration curve



# 7.8.4 Screening curve analysis

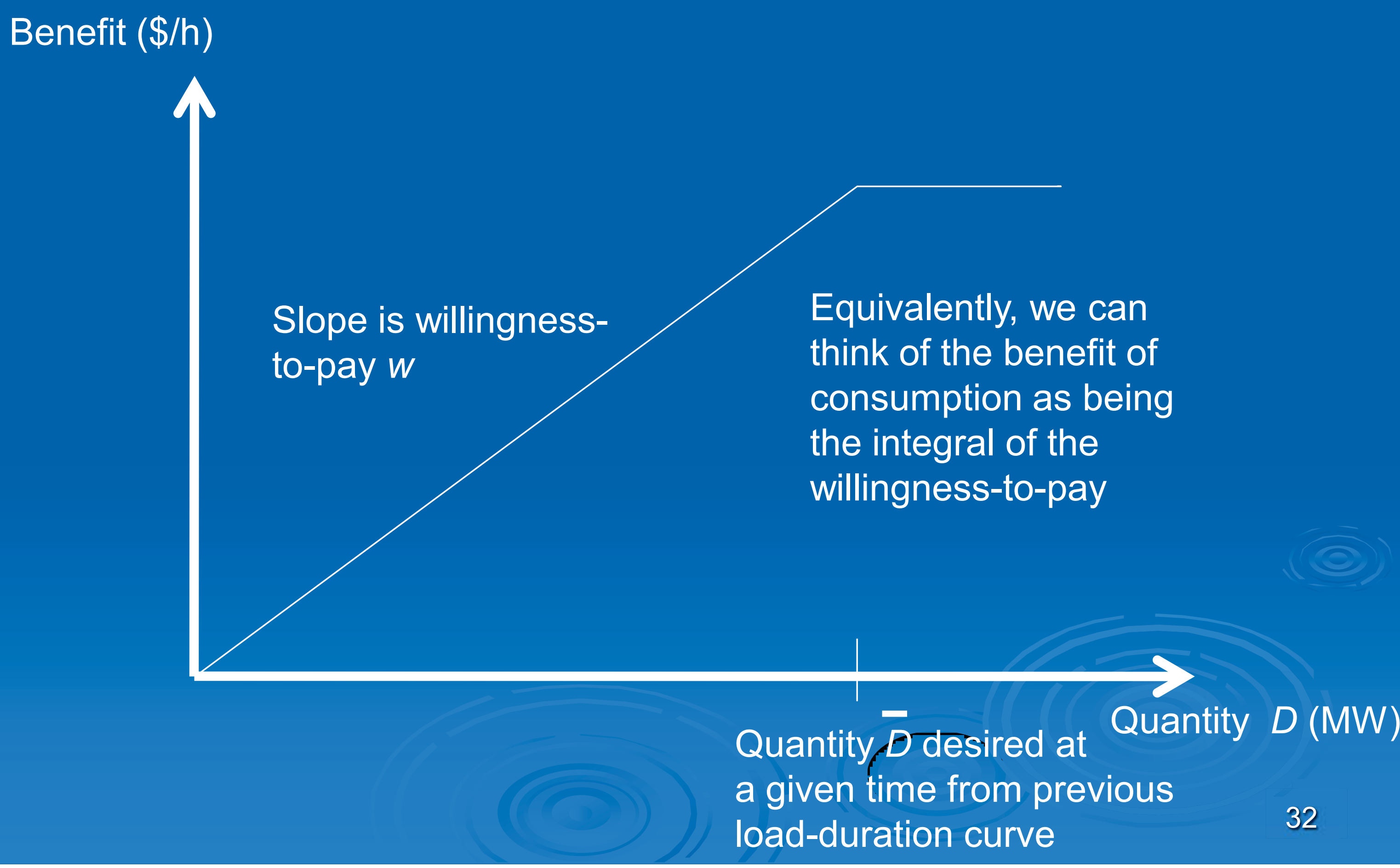
- Analysis using the load-duration curve and the cost of capacity is called a **screening curve analysis**.
- Basic screening curve analysis suggests building enough capacity to meet all demand:
  - Consistent with assumption of fixed demand at each time,
  - with arbitrarily large valuation of benefits of consumption.

# 7.8.5 Price-responsive demand

- However, now suppose that there is price responsiveness of demand.
- In general, this would mean that at each time there is a demand curve.
- Simplified example:
  - For each time, demand has a fixed willingness-to-pay $w$ for demand $D$ up to the previously assumed level of demand $\overline{D}$ on the load-duration curve at that given time,
  - $w$ may correspond to the “dis-benefit” of involuntary curtaliment, or **value of lost load**.
  - Zero willingness-to-pay for higher demands.

# 7.8.6 Demand curve for a particular time

# 7.8.7 Benefit of consumption for a particular time



# 7.8.8 Load-duration curve re-interpreted

- So, we re-interpret the load-duration curve as showing "desired" demand at a given time:
  - If price less than *w* at a particular time then desired amount on load-duration curve is consumed,
  - If price more than *w* at a particular time then consumption falls to zero,
  - If price equal to *w* at a particular time then consumers are *indifferent* between:
    - consuming and paying *w*, or
    - not consuming and paying nothing,
    - so consumption is between 0 and desired amount on load-duration curve.

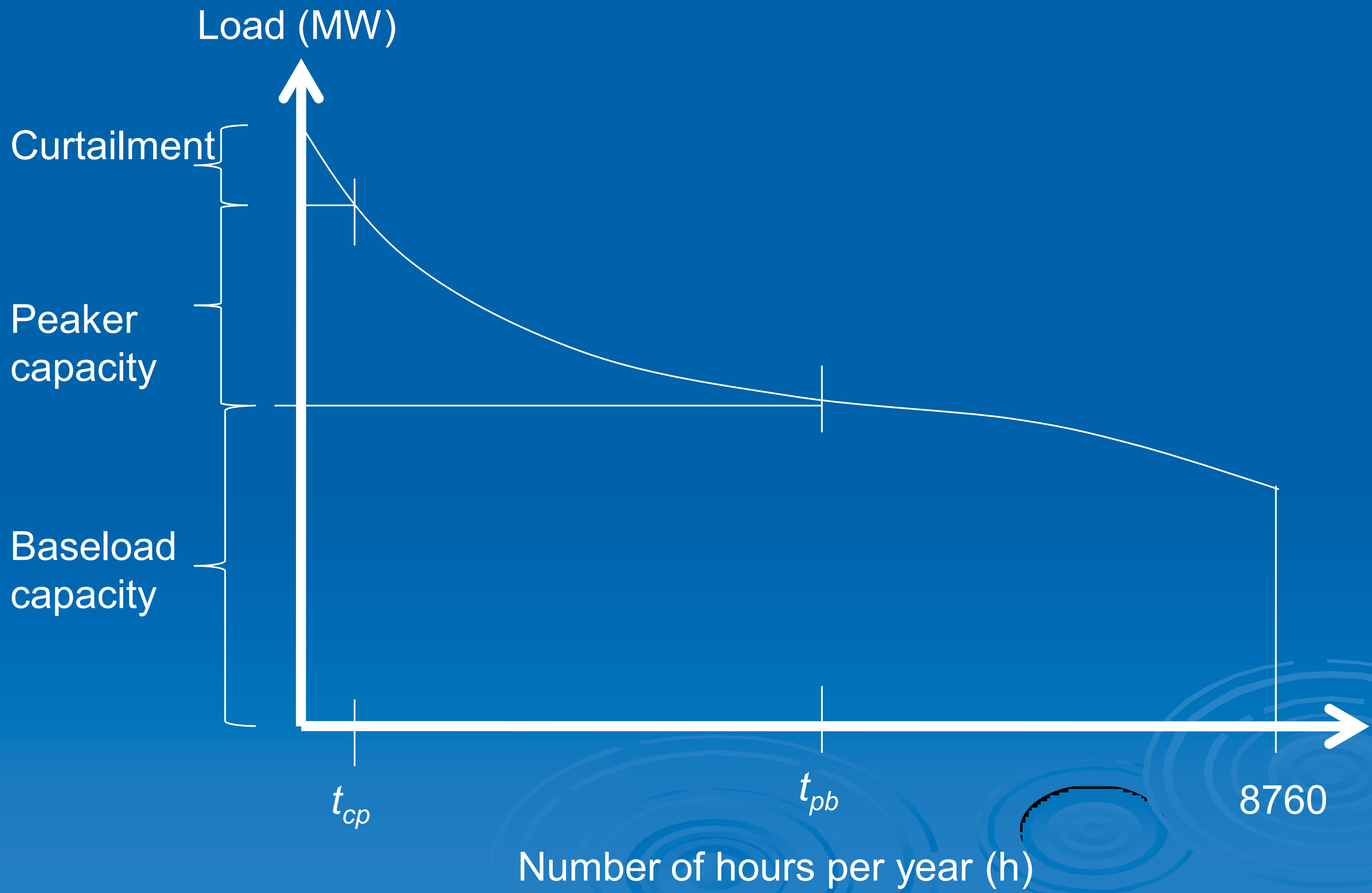
# 7.8.9 Total capacity

- With price responsive demand, what should capacity be?
- Consider a slice of load-duration curve of length $t$ that is near to peak demand and so is supplied by peaker.
- With price responsive demand, willingness-to-pay for this energy is $tw$ per unit capacity.
- Cost of building and operating peaker for this slice is $r_p + t\, c_p$ per unit capacity.

# Total capacity

- Should only supply this demand if *tw* exceeds $r_p + t\, c_p$ per unit capacity.
- If $tw < r_p + t\, c_p$ then benefit of consumption is less than cost of supply and surplus maximization dictates that we should not supply this demand!
- True for small enough value of $t$.
- That is, some demand should be curtailed, and the threshold duration of curtailment $t_{cp}$ is defined by : $t_{cp}\, w = r_p + t_{cp}\, c_p$.

# 7.8.10 Capacity and curtailment under optimal central planning



# 7.8.11 Market

- How would a market achieve this outcome?
  - For both operations and capacity.
- First consider equilibrium prices given some amount of baseload and peaker capacity:
  - We will imagine that infinitesimal slices of generation and slices of demand can bilaterally trade at particular times,
  - Argument will be similar to apartment example,
  - (Will see that practical issues prevent this bilateral trading from occurring literally in context of short-term market operations.)

# 7.8.12 Equilibrium prices

- Consider a particular time when desired amount from load-duration curve is less than baseload capacity:
  - Not all baseload generation is operating,
  - Any generation incurs marginal cost at least $v_b$,
  - So price will be at least $v_b$,
  - Suppose some demand paid more than $v_b$,
  - But then some available (but not generating) baseload generator could undercut this price,
  - So, equilibrium price is exactly $v_b$ and all desired consumption occurs.

# Equilibrium prices

- Consider a particular time when desired amount from load-duration curve is more than baseload capacity and less than sum of baseload and peaker capacity:
  - All baseload generation is operating, but not all peaker capacity is operating,
  - Any generation incurs marginal cost at least $c_b$,
  - If any peaker were paid less than $c_p$ then it would shut down,
  - Similar argument to previous shows that equilibrium price is exactly $c_p$ and all desired consumption occurs.

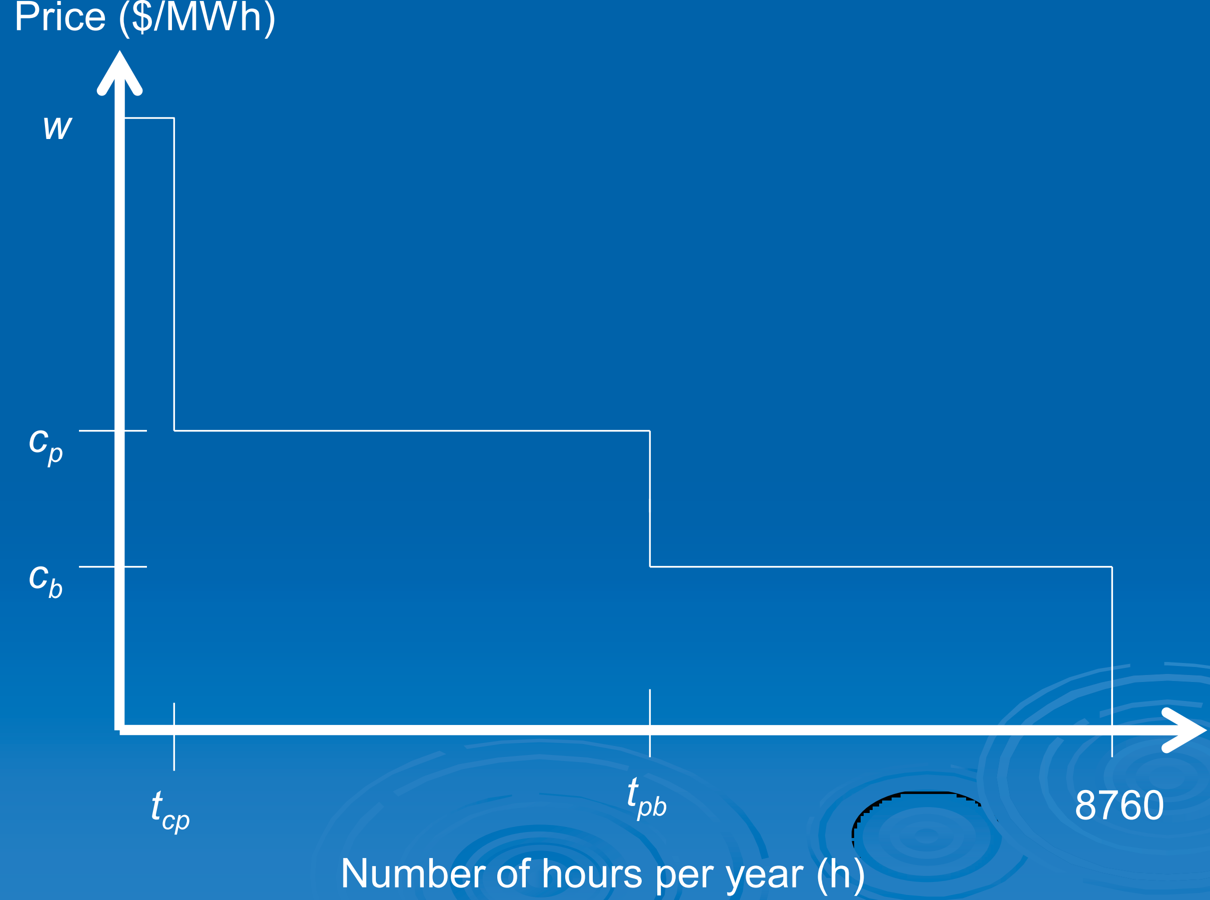
# Equilibrium prices

- Consider a particular time when desired amount from load-duration curve is more than sum of baseload and peaker capacity:
  - Not all desired consumption can occur.
  - Price must be at least *w* in order that not all desired consumption occurs.
  - If price were above *w* then no consumption would occur, but some available generator could undercut this price and sell,
  - Equilibrium price is exactly *w* and consumption equals sum of baseload and peaker capacity.

# Equilibrium prices

- How about if desired consumption exactly equals baseload capacity?
  - Any price from $c_b$ to $c_p$ is an equilibrium price.
- How about if desired consumption exactly equals sum of baseload and peaker capacity?
  - Any price from $c_p$ to $w$ is an equilibrium price.
- So long as these situations occur fleetingly, actual price does not matter:
  - Typical market rules/implementation will fix a particular choice in range.

# 7.8.13 Price-duration curve



# 7.8.14 Lagrange multipliers from central planner problem

- Consider surplus maximization problem faced by central planner at a particular time:
  - Maximize benefits minus operating costs,
  - Lagrange multiplier on power balance between supply and demand would equal the prices we have just calculated,
  - In cases where there is a range of equilibrium prices, there is also a range of possible values of Lagrange multipliers in optimization problem:
    - Software will produce a particular value in range.

# 7.8.15 How much capacity is built?

- The equilibrium prices were for a given level of capacity.
- In ideal market, amount of capacity depends on whether or not there is profitable entry of new generation:
  - Imagine starting with zero capacity (curtailment all the time) and calculating profit obtained from building capacity and selling energy,
  - Assume that new construction occurs until profit of additional entry falls to zero.

# How much capacity is built?

- Claim that amount of capacity built by market exactly matches the optimal levels under central planning:
  - Show that there is zero profit for additional entry when level of capacity is at this level.
- To see this, first recall that centrally planned optimal capacity results in:
  - Curtailment for duration $t_{cp}$,
  - Baseload at full capacity and peaking supplying rest of demand for duration $t_{pb}$ - $t_{cp}$,
  - Baseload supplying demand (and peaking out-of-service) for duration 8760 h - $t_{pb}$.

# How much capacity is built?

- Consider three cases:

1. Baseload and peaker capacity exactly equal to optimal centrally planned capacities,
2. Baseload and/or peaker capacities less than optimal centrally planned capacities, and
3. Baseload and/or peaker capacities more than optimal centrally planned capacities.

# How much capacity is built?

- 1. Suppose baseload and peaker capacities were equal to optimal centrally planned capacities.
- Resulting prices would be:
  - $w$ for duration $t_{cp}$, and
  - $c_p$ for duration $t_{pb}$ - $t_{cp}$, and
  - $c_b$ for duration 8760 h - $t_{pb}$.

# How much capacity is built?

- 1. Given capacities equal to optimal centrally planned capacities, consider a peaker operating for a total time $t$.
- Note that $t_{cp} < t \leq t_{pb}$,
- Revenue of peaker per unit capacity is: $w\, t_{cp} + c_p\, (t - t_{cp}) = r_p + t\, c_p$ ,
- Total costs are the same as revenue per unit capacity,
- So existing (and new) peakers just break even and no additional entry would occur.

# How much capacity is built?

- 1. Given capacities equal to optimal centrally planned capacities, consider a baseload operating for a total time $t$.
- Note that $t_{pb} < t \leq 8760$ h,
- Revenue of baseload per unit capacity is:

  $w\, t_{cp} + c_p\, (t_{pb} - t_{cp}) + c_b\, (t - t_{pb})$

  $= r_p + t_{pb}\, c_p + c_b\, (t - t_{pb})$, (peaker case),

  $= r_b + t_{pb}\, c_b + c_b\, (t - t_{pb}) = r_b + c_b\, t.$
- Total costs are the same per unit capacity,
- So baseload just breaks even!

# How much capacity is built?

- 2. If total capacity is less than centrally planned optimal then:
  - price is *w* for more than optimal duration $t_{cp}$ and peaker revenue would exceed total costs,
  - New peaker entry to would occur, which would tend to reduce curtailment duration towards $t_{cp}$.
  - Similarly, baseload entry will be profitable if duration of prices above baseload operating costs is more than enough to cover capital carrying cost.

# How much capacity is built?

- 3. If capacity is more than centrally planned optimal, then:
  - price is $w$ for less than optimal duration $t_{cp}$ and peaker revenue does not cover total costs,
  - Peakers would "exit" market and curtailment duration would increase towards $t_{cp}$.
  - Similarly, baseload exit will occur if duration of prices above baseload operating costs is insufficient to cover capital carrying cost,
  - (In practice, generation capital is "sunk," so owner may wait until demand increases!)

# How much capacity is built?

- In equilibrium of capacity and operations, amount of peaker and baseload capacity is exactly sufficient to achieve optimal duration of curtailment.
- Conclusion is that market prices will induce optimal capacity and operations:
  - Depends crucially on *curtailment* and that *demand sets price* during curtailment,
  - Will see that an alternative to curtailment could be for demand to set price as part of a voluntary choice not to consume.

# How much capacity is built?

- Arguments can be extended to include uncertain demand and supply:
  - Entry will occur in response to *expectations* about future prices,
  - Possibly adjusted by "risk premium."
- Uncertainty in future prices can be reduced through longer-term bilateral contracts:
  - Including future and forward contracts as discussed in Chapter 6,
  - Will discuss further in Chapter 11.

# 7.8.16 How big is *w*?

- Historically, before the advent of markets, most demand was exposed to a single price over extended periods of time:
  - Curtailment is unsatisfactory in this context.
- Given a fixed price, adjusting demand involves involuntary, rolling blackouts or is in response to public appeals to conserve:
  - Typically think of *w* as being very high in this case, on the order of thousands of $/MWh,
  - Resulting duration of optimal curtailment is very small, with a "traditional" rule of thumb of one day in ten years.

# How big is *w*?

- In the presence of exposure to changing market prices, it is likely that many consumers may be willing to voluntarily forego consumption at relatively lower prices.
- However, most initial electricity market designs have not included mechanisms to elicit willingness-to-pay from demand:
  - ERCOT nodal allows demand bids in day-ahead market, but not in real-time.

# How big is *w*?

- Without knowledge of demand willingness-to-pay, we must base estimates of optimal capacity on indirect measures.
- Problematic issue in ERCOT nodal market!
- Incorporating more demand price responsiveness is an important goal for all markets:
  - Particularly in realistic case of demand *uncertainty.*

# How big is *w*?

- Moreover, even in restructured markets such as ERCOT, involuntary curtailment of demand is typically not politically acceptable.
- In addition to delivering energy, ISOs also procure ancillary services:
  - Focus of “curtailment” then is typically on having less than “full” levels of ancillary services,
  - “Demand curve for reserves” will be discussed in Chapter 8.

# 7.9 Bilateral contracts versus auctions

- Although the idealized market involves bilateral trades, this is not realistic for a short-term market:
  - As will be discussed further, total supply-demand balance must be maintained by a system operator,
  - Necessitates that real-time dispatch and pricing is determined by system operator rather than purely by bilateral trading,
  - Accomplished by an **auction**.

# Bilateral contracts versus auctions

- Bilateral trades common in longer-term contexts:
  - Bilateral trades can be scheduled into day-ahead market,
  - Longer-term bilateral contracts range from hours to decades,
  - Important role in providing collateral to obtain finance to build new generators.
- In Chapter 8, we will focus on auctions for short-term electricity operations.

# Summary

- Construction and operation,
- Central planning versus markets,
- Goals of decision-making,
- Central planning,
- Markets,
- Market idealizations,
- Competition in electricity,
- Ideal central planning,
- Bilateral contracts versus auctions.

# Reference:

- “Competition in Generation: The Economic Foundations,” Richard Green, *Proceedings of the IEEE*, 88(2):128—139, February 2000.

# Homework exercise

7.1

- Download and install PowerWorld,
- Download the 3 Bus System and the 13 Bus System,
- Vary the load in the 3 Bus System in 50 MW increments from 100 MW to 600 MW.
- What is the price at each load level?
- What is the range of equilibrium prices for demand 300 MW and 500 MW?