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. Effect of renewables,
11. Homework exercises.

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 (see Exercise 7.2),
  - 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 below 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, Midcontintent, SPP.
- Retail competition also in place in some jurisdictions, including:
  - United Kingdom, Australia,
  - ERCOT, several other 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" (so ignore possibility of excess generation capacity compared to optimal),
  - uncertainties in demand, fuel costs, investment costs, and in the availability of generators, and
  - the effects of the transmission system.
- Assume that capital cost of generator can be "paid off" on an annual basis.

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,
  - About \$75,000/MW.year for peaker in ERCOT.
- 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.

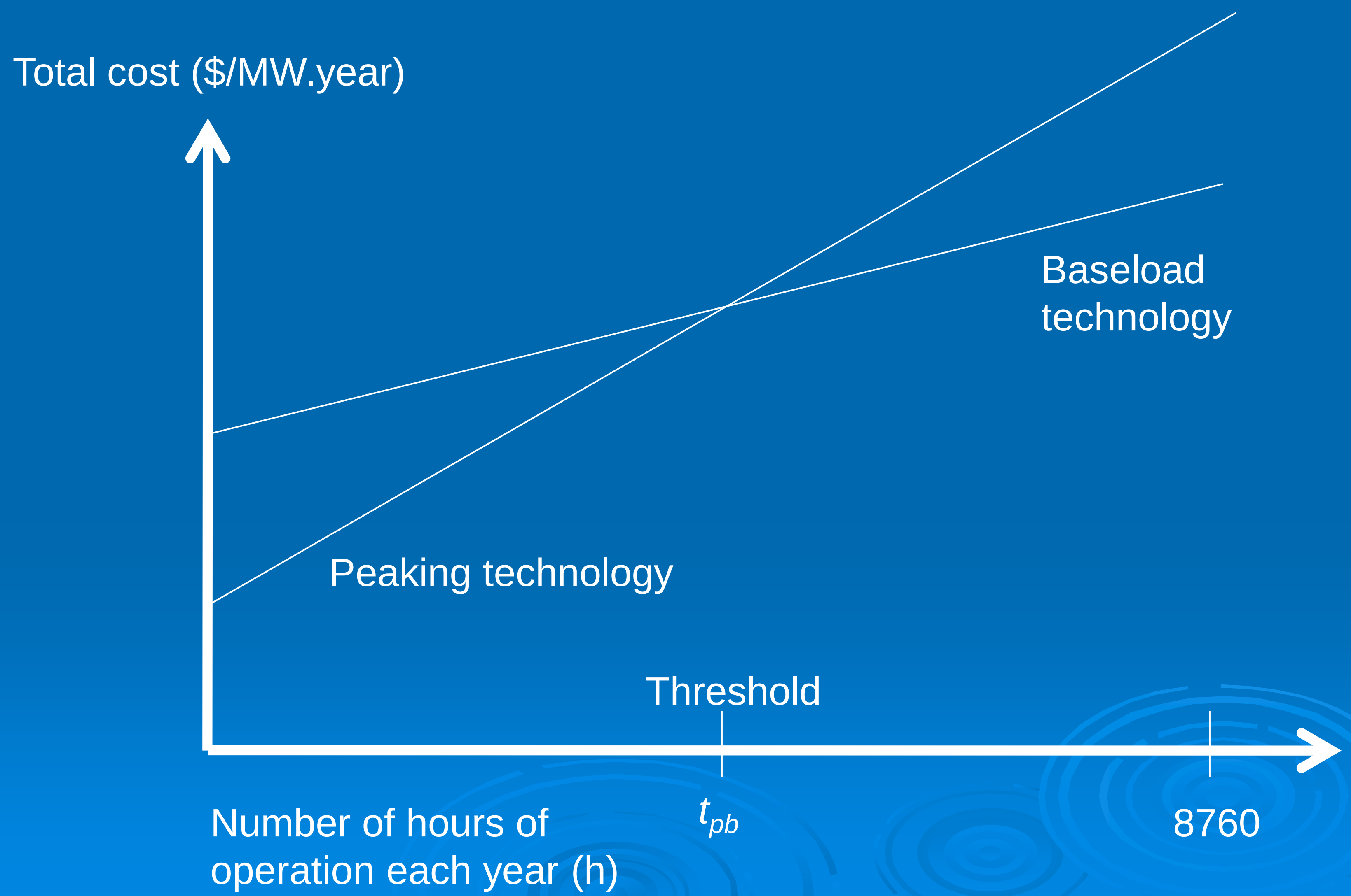
Generator total costs

- 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,
  - Exercise 7.3 considers three types of generation capacity: baseload, intermediate, and peaker.

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: $r_p + t_{pb} c_p = r_b + t_{pb} c_b$.

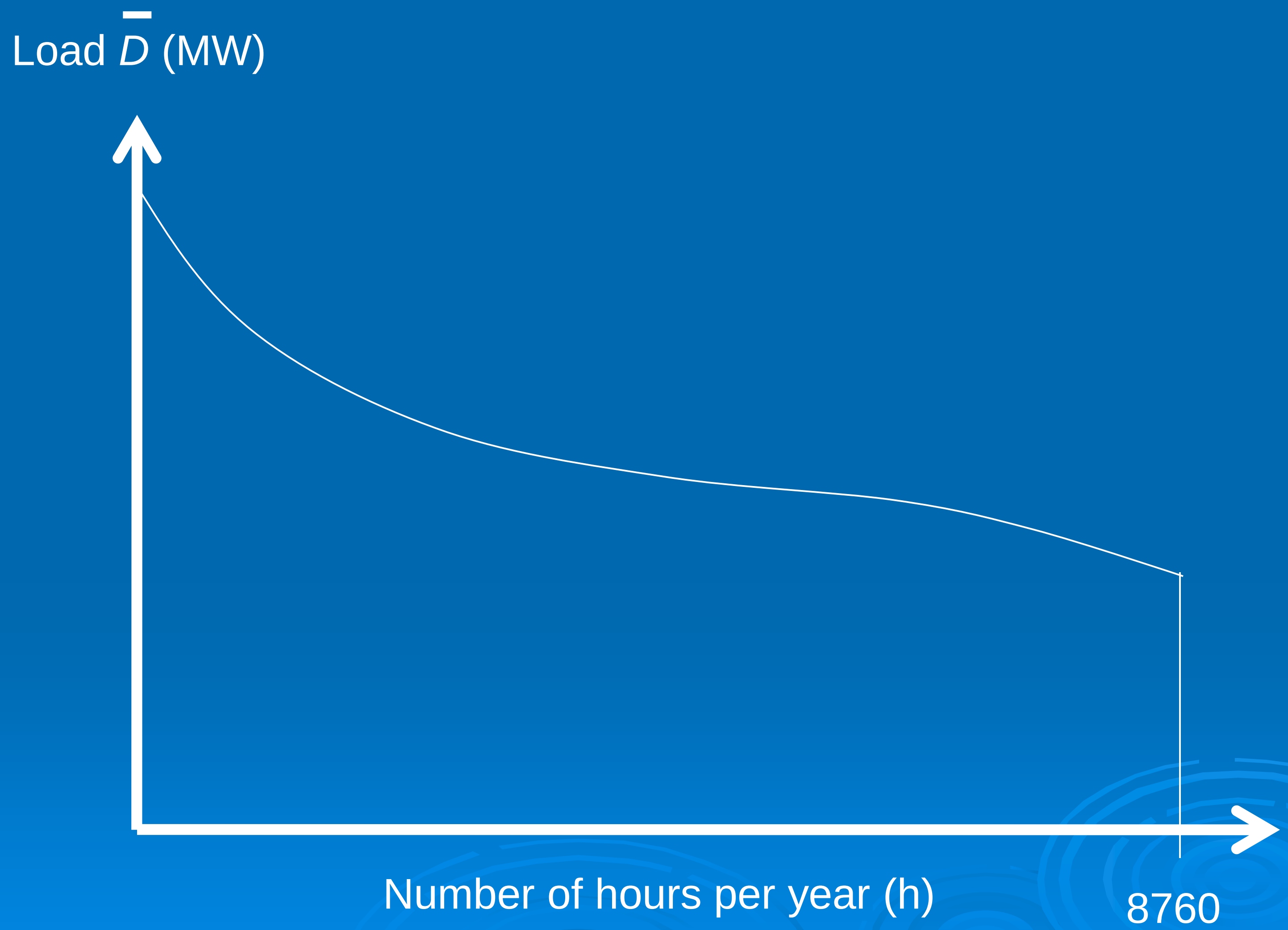
Generator total costs



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.

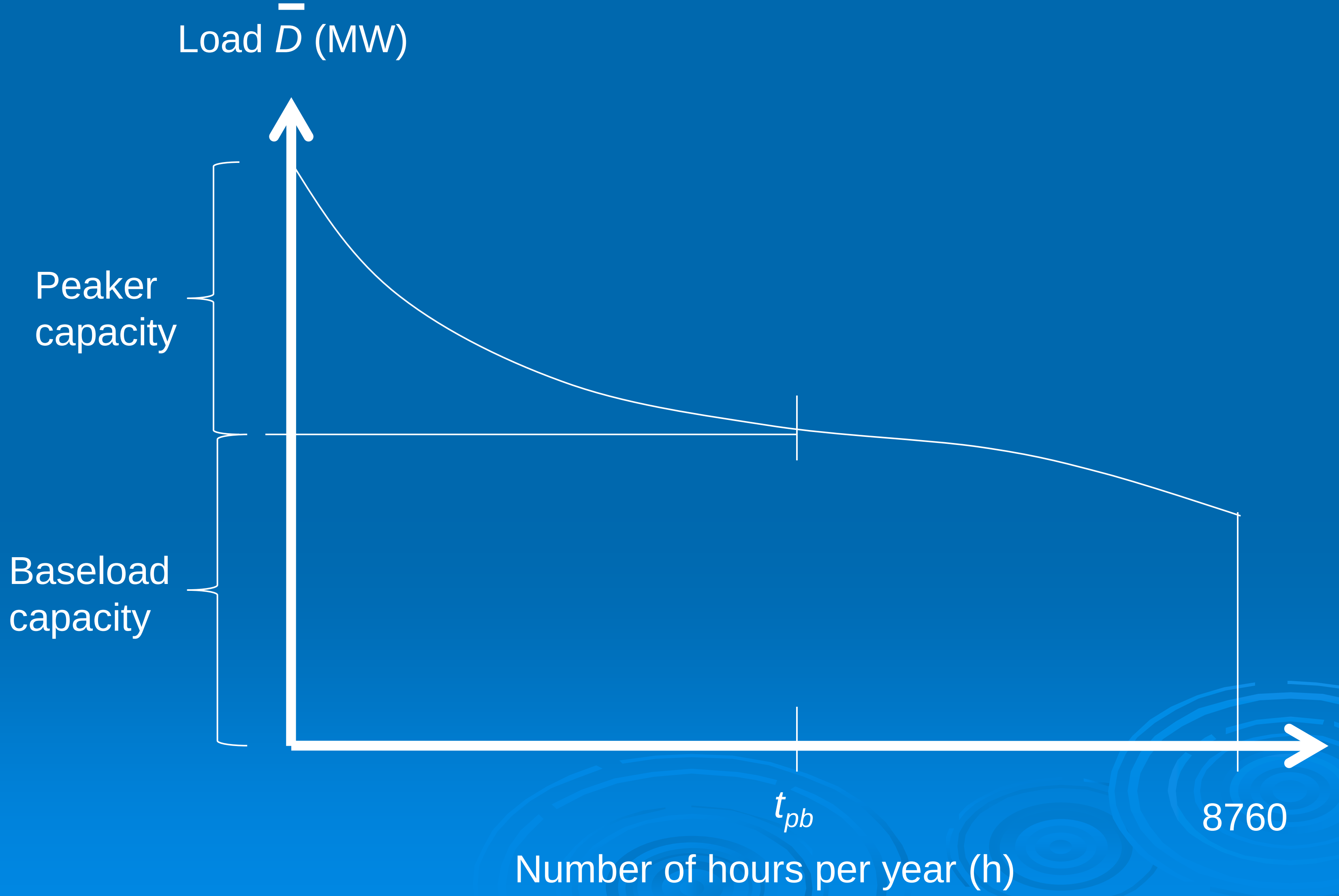
Load-duration curve



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



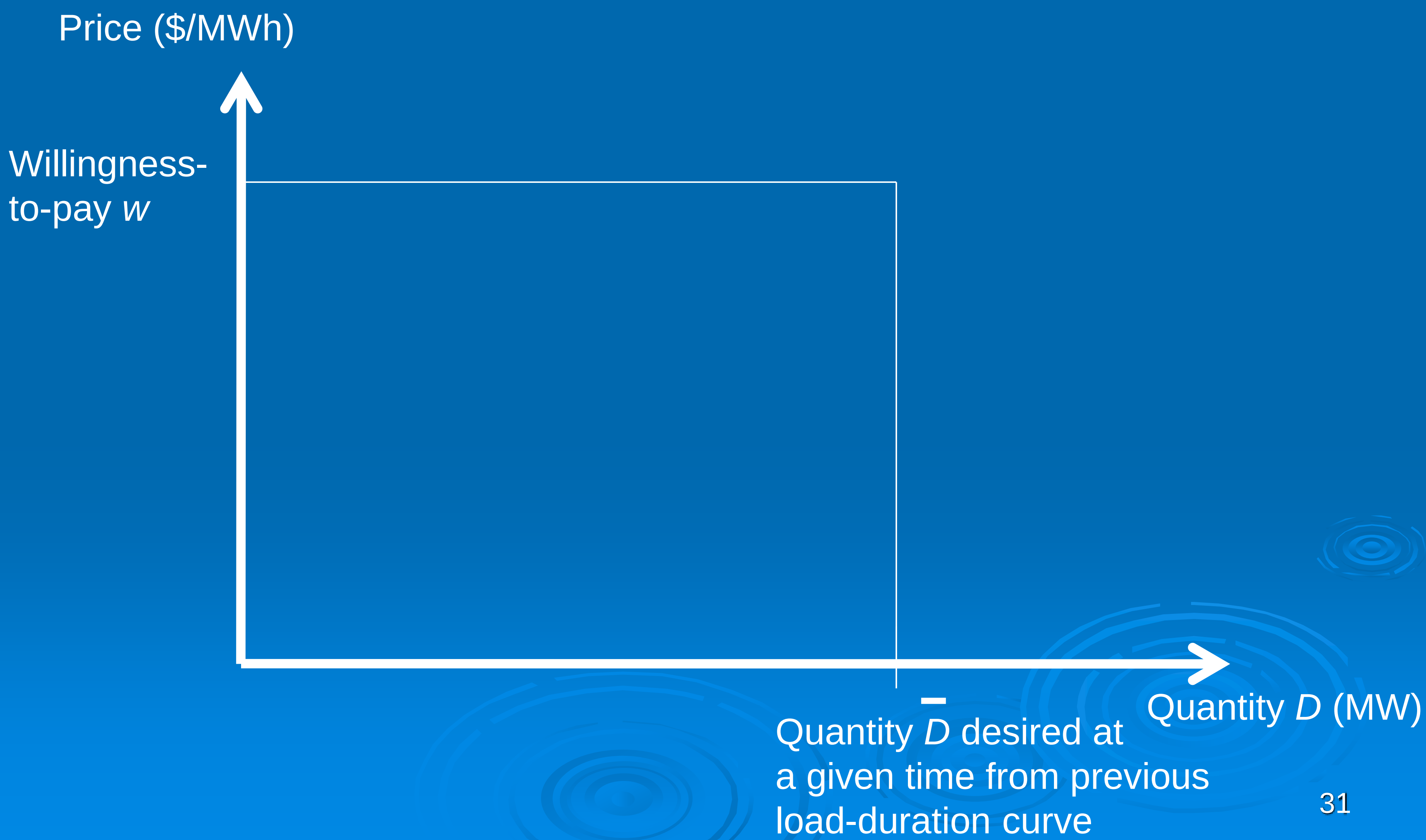
7.8.4 Screening curve analysis

- 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,
  - See Exercise 7.3.

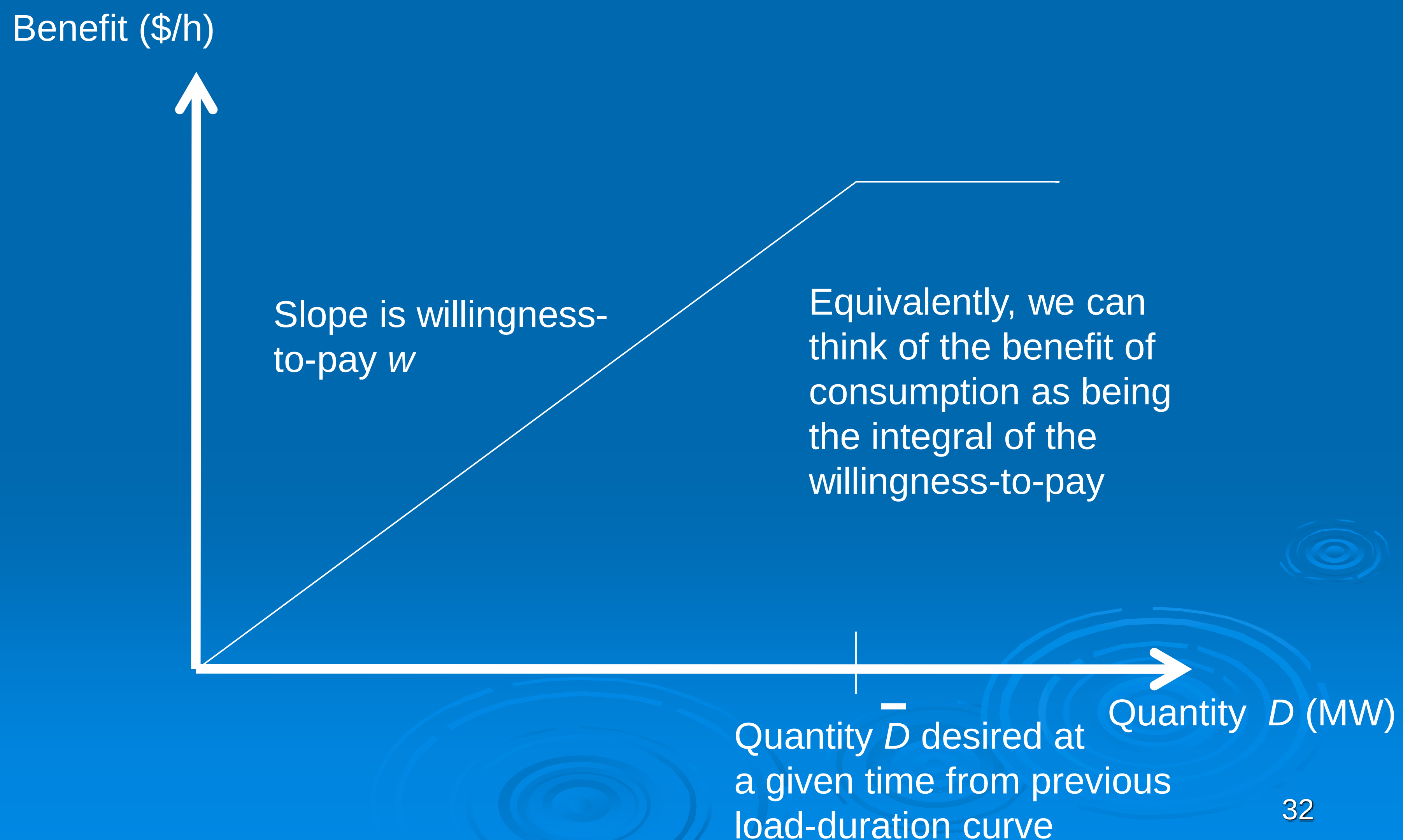
7.8.5 Price-responsive demand

- 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 $\bar{D}$ 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 the desired amount on load-duration curve.

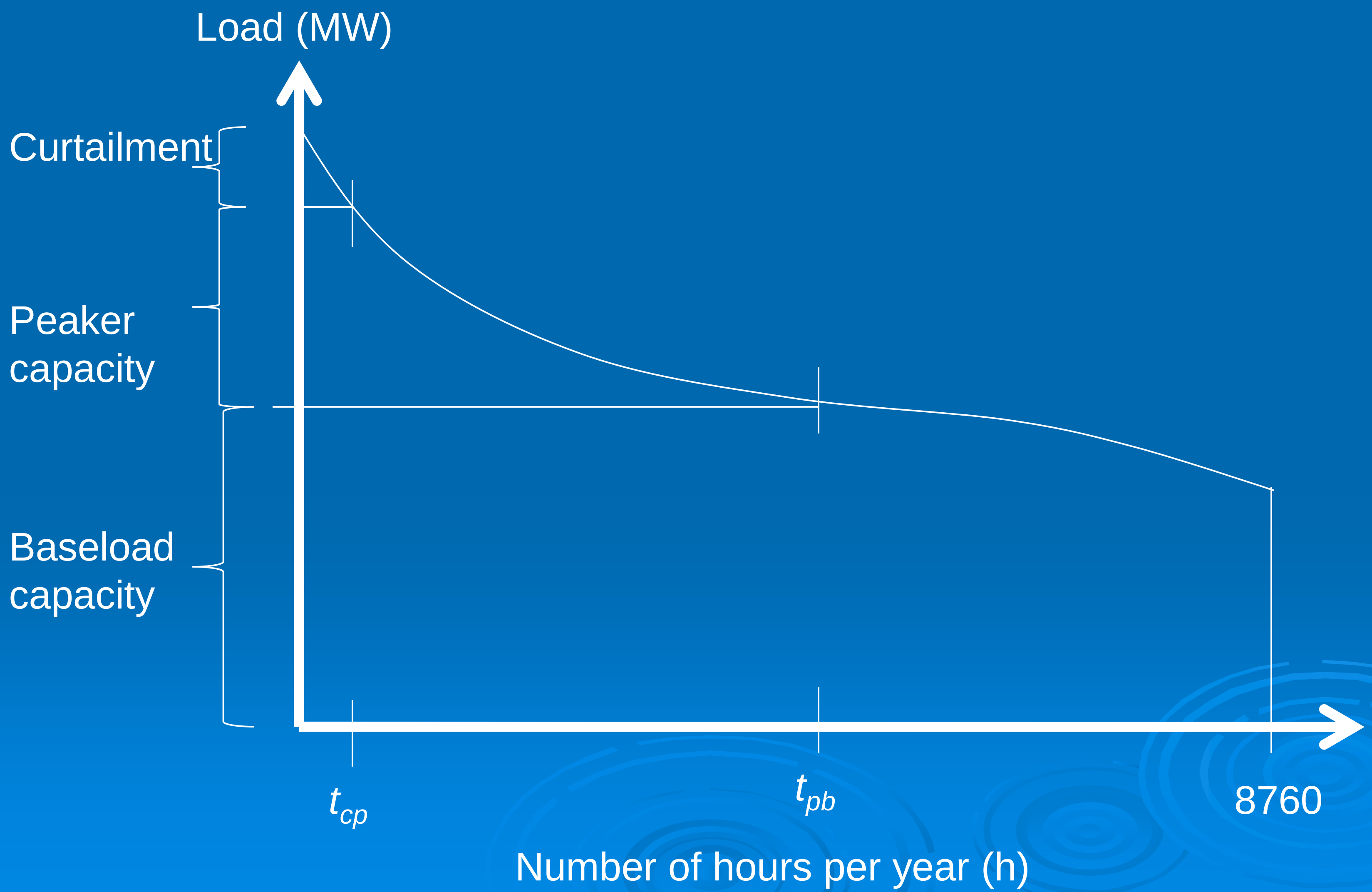
7.8.9 Total capacity

- 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 (the market clearing 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 Market clearing 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 c_b,
  - So price will be at least c_b,
  - Suppose some demand paid more than c_b,
  - But then some available (but not generating) baseload generator could undercut this price,
  - So, market clearing price is exactly c_b and all desired consumption occurs.

Market clearing 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 market clearing price is exactly c_p and all desired consumption occurs.

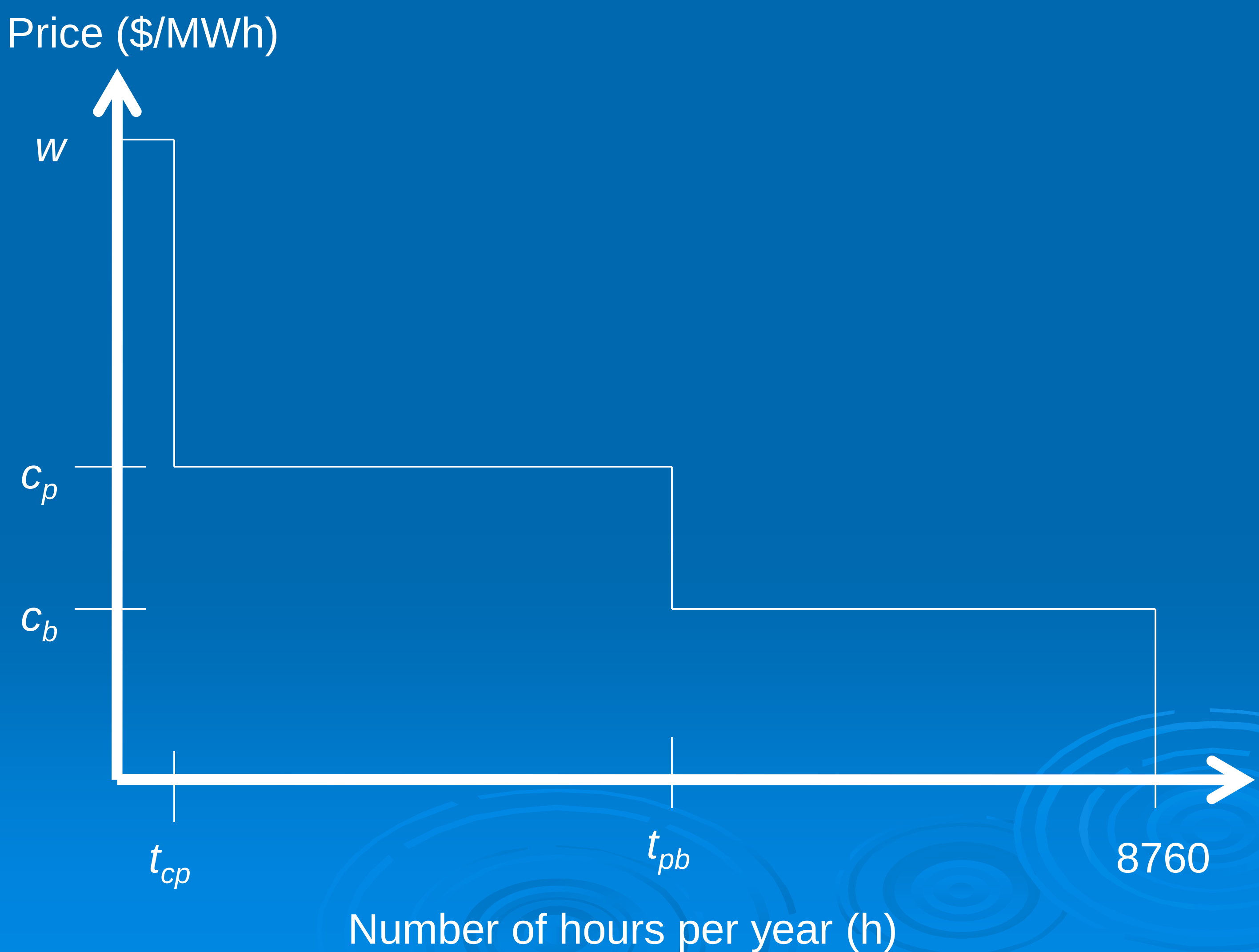
Market clearing prices

- 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,
  - Market clearing price is exactly *w* and consumption equals sum of baseload and peaker capacity.

Market clearing prices

- How about if desired consumption exactly equals baseload capacity?
  - Any price from c_b to c_p is a market clearing price.
- How about if desired consumption exactly equals sum of baseload and peaker capacity?
  - Any price from c_p to w is an market clearing 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 market clearing 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 market clearing 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:

$$w\, t_{cp} + c_p\,(t_{pb} - t_{cp}) + c_b\,(t - t_{pb})$$
$$= r_p + t_{pb}\, c_p + c_b\,(t - t_{pb}), \text{ (peaker case)},$$
$$= r_b + t_{pb}\, c_b + c_b\,(t - t_{pb}) = r_b + c_b\, t.$$

- 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 only limited implementation 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 in market designs:
  - *w* can default to maximum allowed price in market, which is administratively set.
- 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.

7.10 Effect of renewables

- Renewable capital costs of continue to decrease:
  - Eventually expect annual total cost per unit renewable capacity to be similar to annual total cost per unit thermal capacity for both capital and operating, particularly if carbon is priced.
  - But most renewables today have been built under various subsidy schemes,
  - So assume level of renewables to be exogenous,
  - Lack of renewable dispatchability suggests modeling as reduction in demand: “net load.”

Effect of renewables

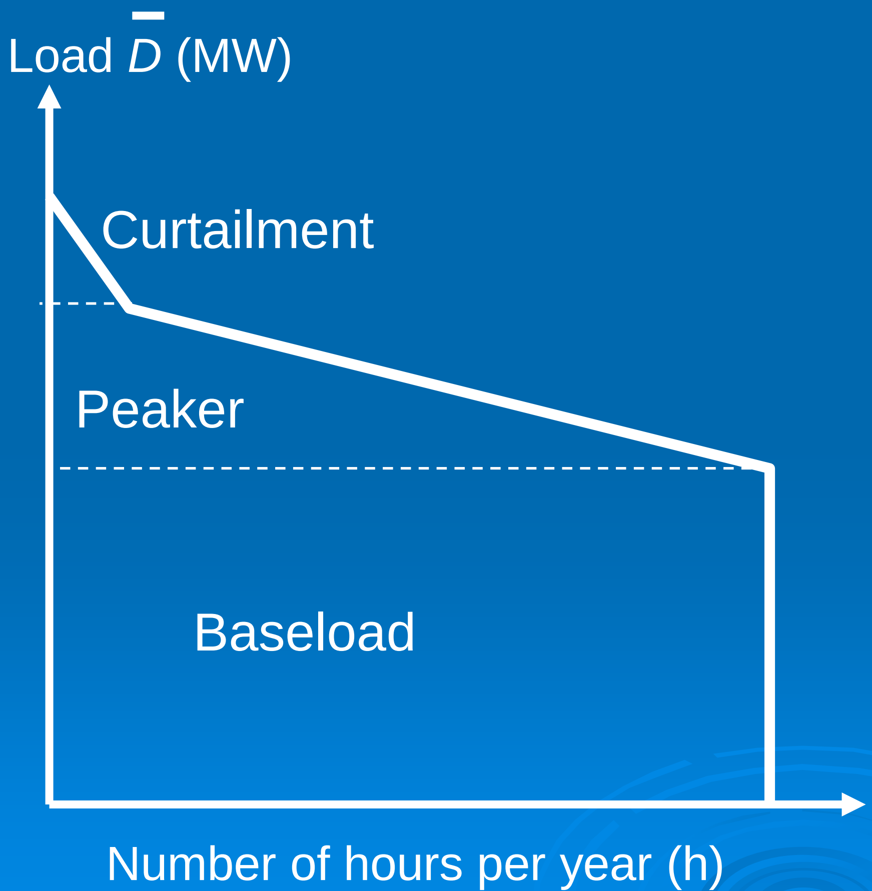
- Net load = load $\bar{D}$ minus renewable production $\bar{W}$.
- Renewable production is typically not aligned with peak consumption:
  - Peak of net load is nearly as high as peak of load, but
  - Minimum of net load is significantly less than minimum of load.

Effect of renewables

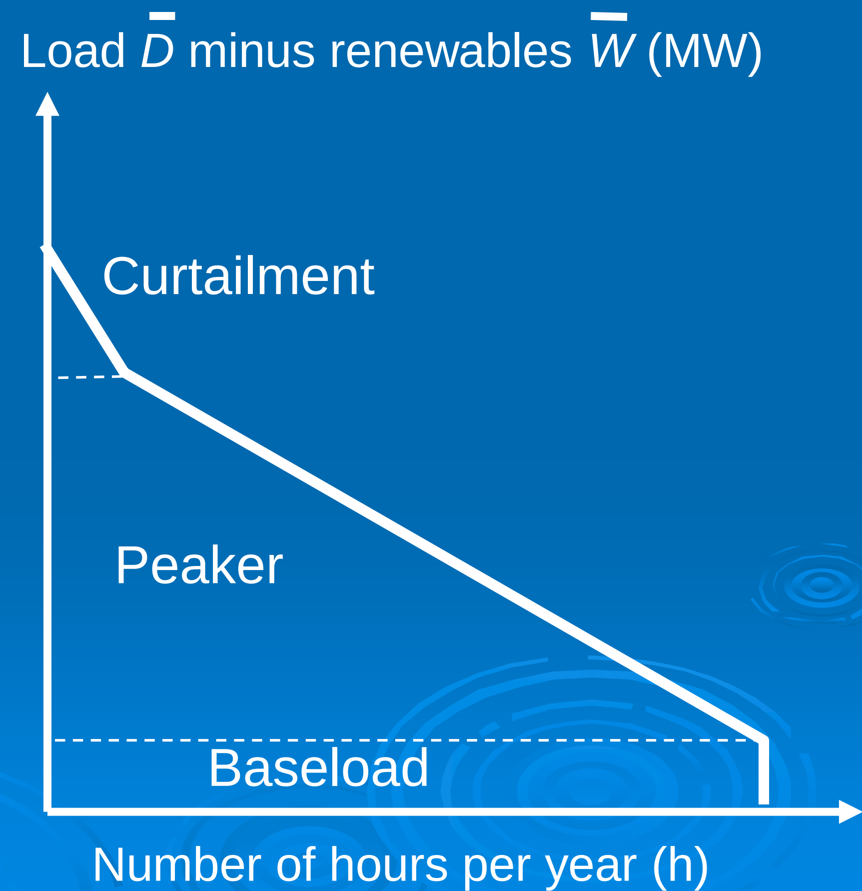
- Under idealized central planning need less baseload generation with renewables:
  - See exercise 7.3.
- In practice, growth in renewables may occur faster than the time needed for thermal system to adapt:
  - “Excess” baseload capacity will not immediatety retire, but may be exposed to low prices,
  - Current concerns about coal and nuclear retirements.

Effect of renewables

Load-duration without renewables.



Net Load-duration with renewables.
Net load = load minus renewables.



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,
- Effect of renewables.

Reference:

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

Homework exercises: 7.1.

- Download and install PowerWorld,
- Download the 3 Bus System and the 13 Bus System from the course website, http://users.ece.utexas.edu/~baldick/classes/394V/EE394V.html.
- Vary the load in the 3 Bus System in 50 MW increments from 100 MW to 600 MW.

1. What is the price at each load level?
2. What is the range of market clearing prices for demand 300 MW and for demand of 500 MW?

Homework exercises: 7.2.

- Consider again the example economic dispatch problem from Section 5.4.1, with $n = 3$ generators and quadratic costs:
- $\forall P_1 \in [0,10]$, $f_1(P_1) = (P_1)^2 \times 0.5$ \$/(MW)^{2}h,
- $\forall P_2 \in [0,10]$, $f_2(P_2) = (P_2)^2 \times 1$ \$/(MW)^{2}h,
- $\forall P_3 \in [0,10]$, $f_3(P_3) = (P_3)^2 \times 1.5$ \$/(MW)^{2}h.
- These costs are based on fuel costs alone and do not include any emissions costs.

Homework exercises: 7.2.

- Suppose that in addition to the direct fuel costs, the generation also imposes additional emissions costs on the environment that can be evaluated by the following functions:
- $\forall P_1 \in [0,10]$, $g_1(P_1) = (P_1)^2 \times 1$ \$/(MW)^{2}h,
- $\forall P_2 \in [0,10]$, $g_2(P_2) = (P_2)^2 \times 0$ \$/(MW)^{2}h,
- $\forall P_3 \in [0,10]$, $g_3(P_3) = (P_3)^2 \times 0.5$ \$/(MW)^{2}h.

Homework exercises: 7.2.

1. What are the fuel costs from the dispatch solution in Section 5.4.1.
2. What are the total costs (that is, fuel costs plus environmental costs) for this solution?
3. Solve the problem of minimizing total costs, including fuel plus environmental costs. What are the total costs?
4. Can economic dispatch minimize total costs without representing the environmental costs?

Homework exercises: 7.3.

- In this exercise, we will consider a screening curve analysis under varying levels of renewables.
- Download and unzip the Screening Curve Application (Windows only) from: http://users.ece.utexas.edu/~baldick/screening_curve_method_tool/scm.html
- Open the SCM_Tool folder and start GenerationPlanning application.
- Under File, select Load Project, and choose the Default Project.

Homework exercises: 7.3.

- Click the setup menu, and under simulation type, make sure that "Capacity Expansion w/o Existing Capacity" is clicked.
- Go to “New Tech” to see that the three technologies available are:
  - Coal, representing the “baseload” technology,
  - Combined Cycle (CC), representing the “intermediate” technology, and
  - Combustion Turbine (CT), representing the “peaker” technology,
  - Curtailment is not considered.

Homework exercises: 7.3.

- Go to “Load” to check that “Wind Scale” is set to 100%:
  - Uses the same values as the loaded data,
  - Note that the load and the net load chronological data are similar throughout the year.
  - Will vary the “Wind Scale” for various parts of the exercise; with higher wind scale, the net load will be significantly lower than the load.
- Click “Run,” wait for “100% Completed” and then click “Result.”

Homework exercises: 7.3.

1. What is the optimal capacity of coal, CC, and CT with wind at 100%?
2. Change “Wind Scale” to 200%, meaning that the wind chronological data has been doubled compared to the loaded data. What is the optimal capacity of Capacity of coal, CC, and CT with wind at 200%?

Homework exercises: 7.3.

3. Change “Wind Scale” to 300%. What is the optimal capacity of Capacity of coal, CC, and CT with wind at 300%.

4. Explain the trends of coal, CC, and CT.