Northwest Power & Conservation Council

BIENNIAL ASSESSMENT OF THE FIFTH POWER PLAN

COAL-FIRED POWER PLANT PLANNING ASSUMPTIONS

November 2, 2006

Rising natural gas prices and the commercialization of advanced coal technologies has renewed interest in coal-fired generation throughout North America. The choice of technology, fuel and site for a developer considering a coal-fired power plant is no longer simple, however. Whereas "coal-fired generation" once implied a single, mature, fairly standardized technology, now, an array of technologies and technology variations, and external factors, competing and uncertain, govern the choice of fuel, sites and technology. Among these are carbon dioxide (CO_2) control policy, increasing availability of petroleum coke[1], higher gas and oil prices leading to the increased attractiveness of polygeneration[2], mercury control policy, changing technology cost and performance characteristics, technology commercialization rate, federal incentives, water availability and public perception.

Conventional and gasification power plants fuelled by coal are among the bulk power generating technologies that were included in the portfolio analysis of the Fifth Power Plan. Action GEN-7 calls for an option to construct 425 megawatts of coal gasification combined-cycle plant to be secured by 2012, for 2016 earliest operation. If, by early 2007, commercialization of coal gasification technology has not progressed as forecast, the plan calls for a contingent option to construct 400 megawatts of conventional coal generation to be secured by 2010 for mid-2013 earliest operation.

The purpose of this paper is to assess the current status of coal-based power generation technologies, and their cost and performance characteristics, compared to the assumptions used in the development of the Fifth Power Plan. Among the conclusions of this assessment are advanced (super-critical) steam-electric coal technologies are entering the market more rapidly than anticipated, the capital cost assumptions for steam-electric technologies remain reasonable, cost assumptions for integrated gasification combined-cycle (IGCC) power plants should be increased to account for the spare gasifier currently needed to achieve the operating availability expected of future baseload power plants, operating availability assumptions for all new baseload coal technologies should be increased for consistency with current practice, availability of

[1] Petroleum coke is a by-product residual carbonaceous material from the thermal cracking of heavy residual oils during the petroleum refining process. High grade petroleum coke is used for electrodes for electric steel furnaces. Low grade coke is used for manufacturing electrodes for aluminum production and for fuel. Because of the increasing use of heavier crudes and more efficient processing of refinery residuals, US and worldwide production of petroleum coke is growing rapidly. Petroleum coke has a superior heating value (13,460 Btu/lb) and very low ash content compared to coal. This reduces transportation costs. However, depending on the original crude feedstock, it may contain a greater concentration of sulfur and metals, making it a less attractive fuel when burned in conventional boilers. Historically, petroleum coke has been priced at a discount to coal.

[2] A coal gasification plant designed to produce, electricity, synthetic natural gas or synthetic liquid fuels or other products, or combinations of these. Polygeneration capability increases potential revenues and provides greater operational and financial flexibility.

petroleum coke fuel for gasification plants should be considered, the thermal efficiency of IGCC plants will be lower than assumed and the efficiency of supercritical steam-electric plants will be higher than assumed.

Technology and Applications

The two basic types of baseload coal-fired power plants are direct-fired (steam-electric) plants and gasification plants. Direct-fired plants combust coal in a furnace to raise steam that drives a steam turbine-generator. Gasification plants convert coal into a synthetic fuel gas by a partial combustion process. The synthetic gas fuels a combined-cycle gas turbine generator. Both types of plants would be used primarily to supply base load power, though the gasification plant offers the potential for greater operating flexibility. Earlier assessments forecast the thermal efficiency of an integrated gasification combined-cycle (IGCC) plant to be clearly superior to that of direct combustion plants. More recent studies indicate that advanced direct combustion plants using supercritical steam conditions may have efficiencies approaching that of IGCC plants.

Coal gasifiers can utilize biomass and petroleum coke (pure or blended), though the prospective fuels need to be considered in the design of the plant. Direct-fired plants can also be designed for co-firing of biomass and other fuels.

Gasification technology employs pre-combustion cleanup of the synthetic gas stream. This can result in very low air emissions if the necessary cleanup equipment is installed. However, recent advances in emission control technology for direct-fired plants can reduce the air emissions of these plants to levels comparable to gasification plants. Perhaps the greatest advantage of gasification plants is that they can be equipped with relatively proven technology for partitioning carbon dioxide from raw synthetic gas, for subsequent sequestering of the CO_2. Partitioning CO_2 from the post-combustion gases of a direct-fired plant is possible, but in a much earlier stage of development.

Advanced, supercritical direct-fired steam plants are an evolutionary technology, basically being a much higher-pressure version of a conventional steam-electric plant. Early (1960s) supercritical designs proved unreliable because of material failures. Better materials have improved the reliability of these plants and numerous supercritical units are operating in Europe and several are under construction in North America. Gasification technology, while widely used in the petrochemical industry for production of organic chemicals from coal and refinery residues, has not been widely used for power generation. Nor is there much experience gasifying low-rank western coals. Operating availability is a particular concern. Demonstration plants constructed in the 1990's encountered multi-year shakedown period of low availability, though these plants are reported now to operate reliably. Periodic replacement of the refractory lining of the gasifiers is needed, a process requiring several weeks. To maintain adequate availability for power generation, proposed gasification power plant designs now incorporate spare gasifiers.

Cost and Performance Assumptions

Key Fifth Power Plan planning assumptions for coal-fired power plants are shown in the following table. Project output and costs are based on ISO conditions.[3] Costs are adjusted to 2006 dollars for better comparability to current conditions. Heat rates and costs are normalized for 2010 service.

[3] Sea level, 59^{o}F. Output and costs were adjusted for higher elevation situations in the 5th Plan analyses.

	Direct-fired Subcritical	Direct-fired Supercritical	IGCC (w/o CO_2 Partitioning)	IGCC (w/ CO_2 Partitioning)[4]
Type	400 MW sub-critical pulverized coal-fired, evaporative cooling. Low-NOx burners, flue gas desulfurization, fabric filter w/ activated charcoal injection	400 MW supercritical pulverized coal-fired, evaporative cooling. Low-NOx burners, flue gas desulfurization, fabric filter w/ activated charcoal injection.	425 MW integrated gasification combined-cycle; sulfur stripping unit, activated carbon Hg removal, H-class gas turbine generator.	425 MW integrated gasification combined-cycle; sulfur stripping unit, activated carbon Hg removal, shift reactor & CO_2 stripping unit (90%); F-class gas turbine generator
Net Output	400 MW	400 MW	425 MW	401 MW
Availability	84%	84%	83%	83%
2004 Commercial status	Mature	Emerging Commercial	Demo (F-class GTG) Conceptual (H-class GTG)	Conceptual
Heat Rate[5] (Btu/kWh)	9426	9070	7813	9170
Capital cost ($/kW)[6]	$1435	$1457	$1617	$2079
Fixed O&M cost ($/kW/yr)	$46	$47	$52	$61
Variable O&M cost ($/MW)	$2.00	$2.00	$1.70	$1.80
Development and Construction Schedule	36/42	36/42	36/48	36/48
Earliest service (greenfield site)	2011	2011	2011	2011

Subcritical and supercritical plants were not modeled separately in the Fifth Plan. Rather, they were modeled as a single pulverized coal steam electric technology that improved over time as the penetration of supercritical plants increased. This was assumed to increase the average new plant efficiency by 0.25% annually and also to increase fixed costs by 0.1% annually because of the higher cost of materials required for supercritical designs.

[4] CO2 compressed to critical state at plant fence, no CO2 transportation or sequestration.
[5] ISO, higher heating value, new and clean.
[6] Overnight cost, 2006 dollars.

The gasification plant without CO_2 separation capability was the technology used in the Fifth Plan portfolio analysis. The efficiency of gasification plants was assumed to increase by 0.5% annually, and fixed costs were assumed to decline by 0.5% annually through improvements to gasification and gas turbine technology.

Review of Cost and Performance Assumptions

Significant factors affecting the cost-effectiveness of coal-fired power plants include capital cost, thermal efficiency and operating availability.

Capital cost of direct-fired subcritical power plants

The Fifth Power Plan capital cost assumption for direct-fired subcritical power plants are compared in Figure 1 to announced project costs taken from a data base maintained by the Council, and to recent estimates prepared for the U.S. Environmental Protection Agency and for PacifiCorp. For completed projects and projects under construction, the horizontal axis represents the initial year of construction; for estimates and proposed projects, the horizontal axis represents the year of the estimate. The vertical axis represents "overnight" capital cost[7] in 2006 dollars. The "Subcritical project" series (triangles) are per-kilowatt capital costs, normalized to the definition of overnight costs used in the Fifth Plan. Relatively few coal-fired power plants have been constructed in recent years, leading to the small sample size, even though interest in coal is currently high. Somewhat higher costs are evident for the more recent data points, suggesting the possible effects of recent increases in materials cost.

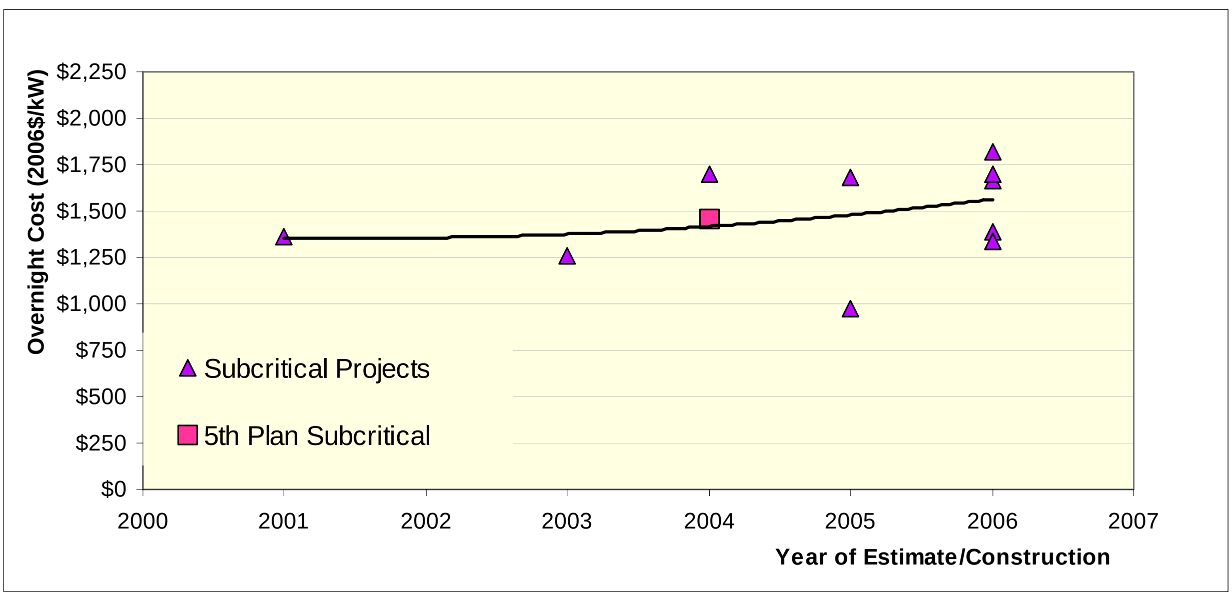

Figure 1: Direct-fired subcritical power plant capital cost estimates

[7] "Overnight" cost is the total construction cost less costs of financing, escalation and interest during construction.

The Fifth Plan cost estimate are shown as the 2004 box. While slightly lower than the average of the 2006 points, the 5th Plan assumption appears to remain reasonably representative of expected long-term market conditions.

Capital cost of direct-fired supercritical power plants

Figure 2 compares capital costs for supercritical steam cycle plants. As before, the recent upturn in costs due to increasing materials costs is evident. The arrows in Figure 2 indicate two examples where plant costs were recently re-estimated as the projects moved forward. Significant cost increase occurred in each case, partly because of refinement and modification of project design, but also because of increasing materials costs.

The Fifth Plan cost estimate is shown as the 2004 box. As before, while slightly lower than the average of the 2006 points, the 5th Plan assumption appears to remain reasonably representative of expected average long-term market conditions.

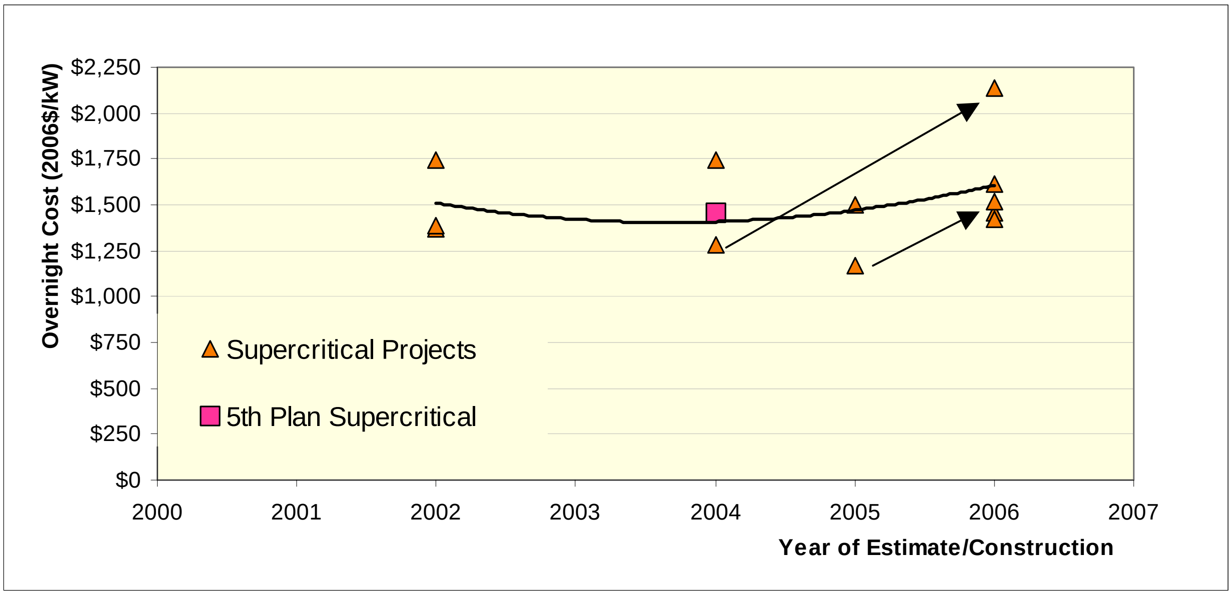

Figure 2: Direct-fired subcritical power plant capital cost estimates

Capital cost of coal gasification combined-cycle power plants

Figure 3 compares capital costs for integrated gasification combined-cycle power plants. These are plants without provision for CO_2 separation, though that capability could be retrofitted subsequent to initial completion. (This is the plant configuration used in the Fifth Plan portfolio analysis.) A general upward cost trend is evident. Though increasing materials costs are a contributing factor, the trend in the case of IGCC plants is also due to more accurate estimates resulting from better definition of plant requirements. (Typically, the costs of emerging power generation technologies are underestimated prior to their actual deployment). Specifically, several recent estimates have included a spare gasifier in order to achieve design plant availabilities in the 90 percent range. In addition, the higher cost 2004 and 2006 examples are for high-elevation plant sites. Gas turbine and air separation plant output decline as site elevation increases because of the additional compressive work required in the lower density ambient air. This increases the per-kilowatt cost of these plants.

The Fifth Plan IGCC cost estimate is shown as the 2004 box. A second box is shown at 2006 representing the Fifth Plan estimate adjusted for the additional cost ($100 - 200/kW) of a spare gasifier to achieve plant availabilities in the 90 percent range. Though comparable to the higher 2006 estimates, the resulting estimate may be slightly high since the Plan assumption is intended to represent a low-elevation site and equilibrium market conditions.

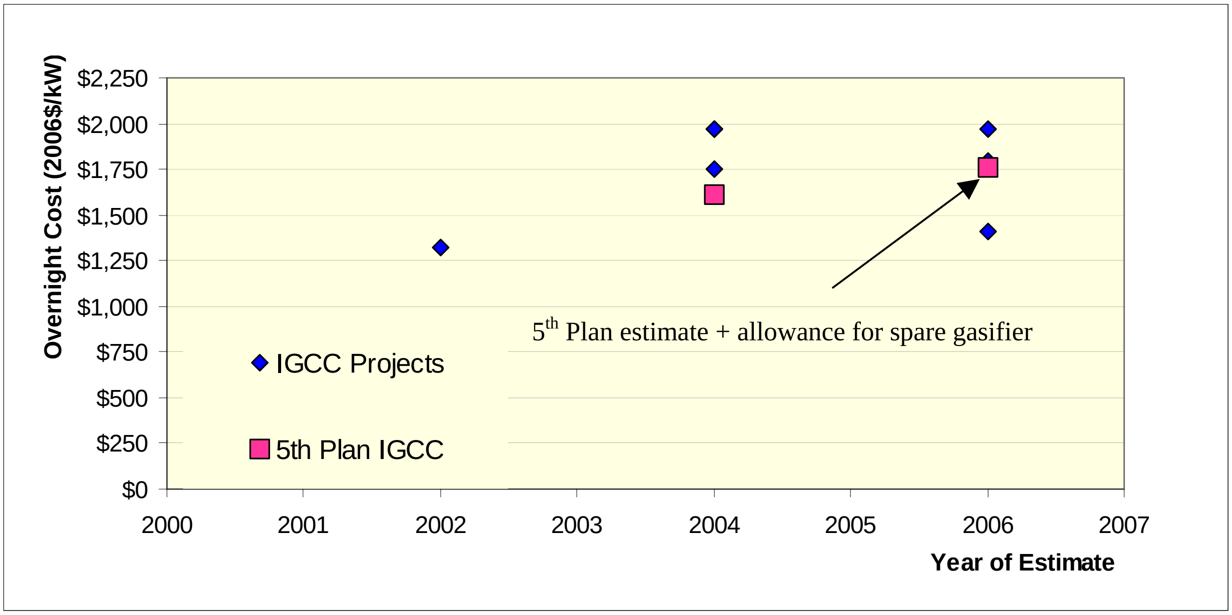

Figure 3: Coal gasification combined-cycle power plant capital cost estimates

Efficiency of coal-fired power plants

As the engineering of coal gasification power plants has advanced in recent years, moving from generic to standardized, coal-specific and site-specific designs, it has become evident that the thermal efficiency of these plants was overestimated in earlier studies. Plotted as blue diamonds in Figure 4 are design and estimated heat rates of IGCC plants. The vertical axis of Figure 4 is heat rate, a measure of the amount of fuel consumed per kilowatt-hour produced. Heat rate is the inverse of thermal efficiency, i.e., as heat rate declines, thermal efficiency increases. The large pale blue diamond to the right represents the Fifth Plan assumption. This estimate, based on studies conducted about year 2000, is representative of earlier studies, is the lowest of the samples. The higher heat rate values to the left are more representative of the design values of current engineering studies. This suggests that the Fifth Plan efficiency assumption for IGCC plants should be increased about 7 percent from 7915 to 8000 Btu/kWh.

The Fifth Plan assumption regarding the heat rate of direct-fired supercritical units, also plotted in Figure 4 (large pink square compared to red squares) appears to underestimate the efficiency of this technology. The plot suggests that the Fifth Plan efficiency assumption for IGCC plants should be lowered about 2 percent from 9070 to 8900 Btu/kWh. Finally, the Fifth Plan estimate of the efficiency of direct-fired subcritical units (Large gray triangle among black triangles in Figure 4) appears to be somewhat optimistic. A 3 percent increase in the assumed heat rate of subcritical units, from 9550 to 9850, appears to be in order.

These changes to heat rate assumptions may appear minor, but in practice can significantly affect the comparative economics of the technologies. The result of these changes is to establish clearly superior economics to supercritical direct fired units compared to subcritical units, and to narrow the fuel cost gap between direct-fired super critical plants and IGCC plants.

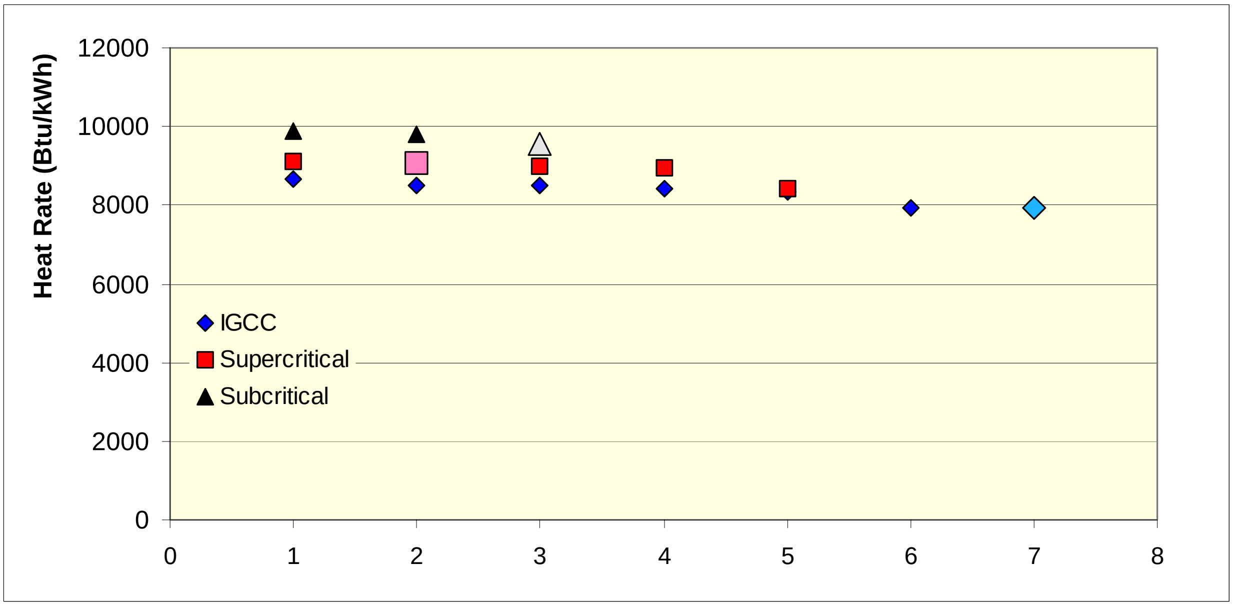

Figure 4: Coal-fired power plant efficiency estimates

Conclusions

The role of coal-fired generation and of the various coal technologies is in ferment. Supercritical steam-electric technology is superceding conventional subcritical technology in the North American market. Commercialization of gasification plants lags that of supercritical plants, but is also advancing. Though currently at an overall cost-of-power disadvantage compared to super critical plants, particularly at high elevation locations, gasification plants retain clear advantages including the potential for polygeneration, commercially-available technology for separation of CO_2, somewhat superior air emission control and less water consumption.

Refinement of IGCC designs has led to the frequent inclusion of a spare gasifier, at increased cost, to achieve the 90% level of availability now expected of baseload plants. Refinement of IGCC designs has also resulted in lower estimates of thermal efficiency for first generation commercial plants.

The Fifth Plan assumptions regarding baseload coal-fired plant availability (~85%) are lower than current expectations (~90%).

Fifth plan capital cost estimates for direct-fired plants (sub- & supercritical) remain reasonable, however the estimates for IGCC plants should be increased to account for a spare gasifier.

Increased availability of petroleum coke, and the availability of commercial coke-fired IGCC technology has created the opportunity for clean plants at Westside locations using low-cost solid fuel.

Capital costs of all coal-fired technologies in the near-term are probably somewhat high because of the increased cost of materials. The Fifth Plan estimates are intended to be representative of loner-term equilibrium market conditions.

The Fifth plan assumptions of coal-fired power plant thermal efficiencies should be revised. IGCC assumptions are about 8% high and direct-fired subcritical assumptions about 3% high. Supercritical assumptions are about 2% low.

"CO_2 removal ready" (CRR) IGCC plants that incorporate the oversized gasification and air separation equipment necessary to ensure the material balance of the retrofit plant may cost about 10 percent more than plants that only reserve space for future retrofit. Future revisions to the power plan should consider this option.

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COAL-FIRED POWER PLANT PLANNING ASSUMPTIONS

Northwest Power & Conservation Council

Power Committee

Coeur d'Alene, ID

November 14, 2006

Purpose

- Identify possibly significant changes to Fifth Plan quantitative planning assumptions regarding coal-fired resources
  - Capital cost ($/kW capacity)
  - Thermal efficiency (as heat rate, Btu/kWh)
  - Operating availability (equivalent annual full power hours as %)
- Identify other developments possibly affecting role of coal-fired plants in the Plan.
  - Commercial status/Earliest service
  - Applications

Technologies & Terminology

Direct-fired ("pulverized coal") steam-electric plant

- Coal (or other solid fuel) burned directly in a furnace to produce steam
- Steam turbine-generator produces power
- Steam conditions (pressure & temp)
  - Subcritical ("Conventional" plant) 2400 psig/1000F/1000F
  - Supercritical 3500psig/1050F/1050F
  - Ultra-supercritical 4500psig/1100/1100

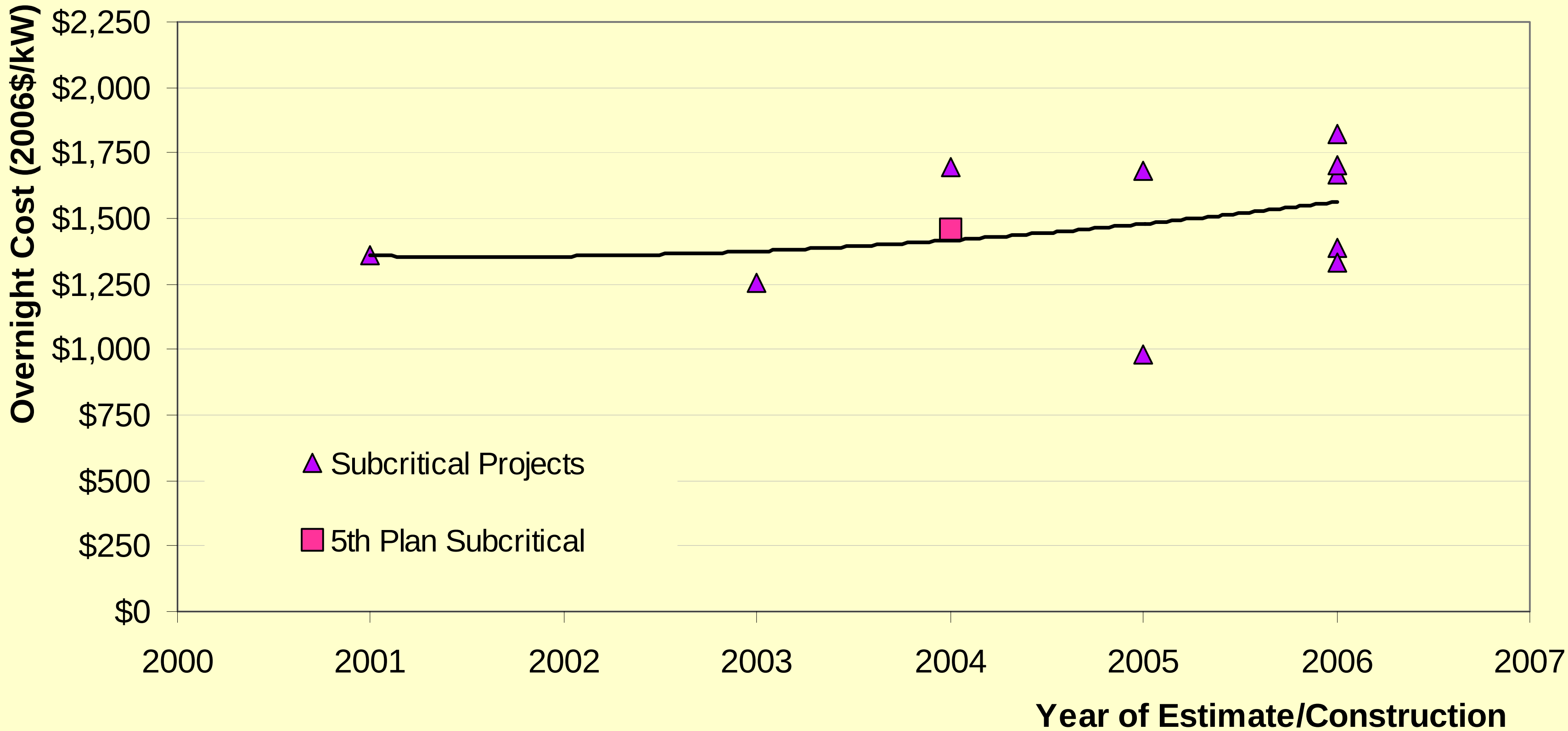
Gasification combined-cycle power plant (IGCC)

- Coal (or other solid fuel) converted to synthetic gas by partial oxidation
- Synthetic gas burned in combined-cycle plant to produce power
- Various gasifier designs, depending on fuel

Technology features

	Subcritical	Supercritical	IGCC
Commercial status	Mature	Early Commercial	Pre-commercial
Applications	Baseload generation	Baseload generation	Baseload generation Co-production
Fuels	Coal Biomass (co-fire)	Coal Biomass (co-fire)	Coal Biomass (co-fire) Petroleum coke
Power generation	Steam turbine	Steam turbine	Combined-cycle
Emission Control	Post-combustion	Post-combustion	Pre-combustion
CO2 Separation (Status)	Oxyfiring (Conceptual) Post-combustion (Conceptual)	Oxyfiring (Conceptual) Post-combustion (Conceptual)	Pre-combustion (Commercial in chemical industry)

Capital cost: Subcritical steam-electric



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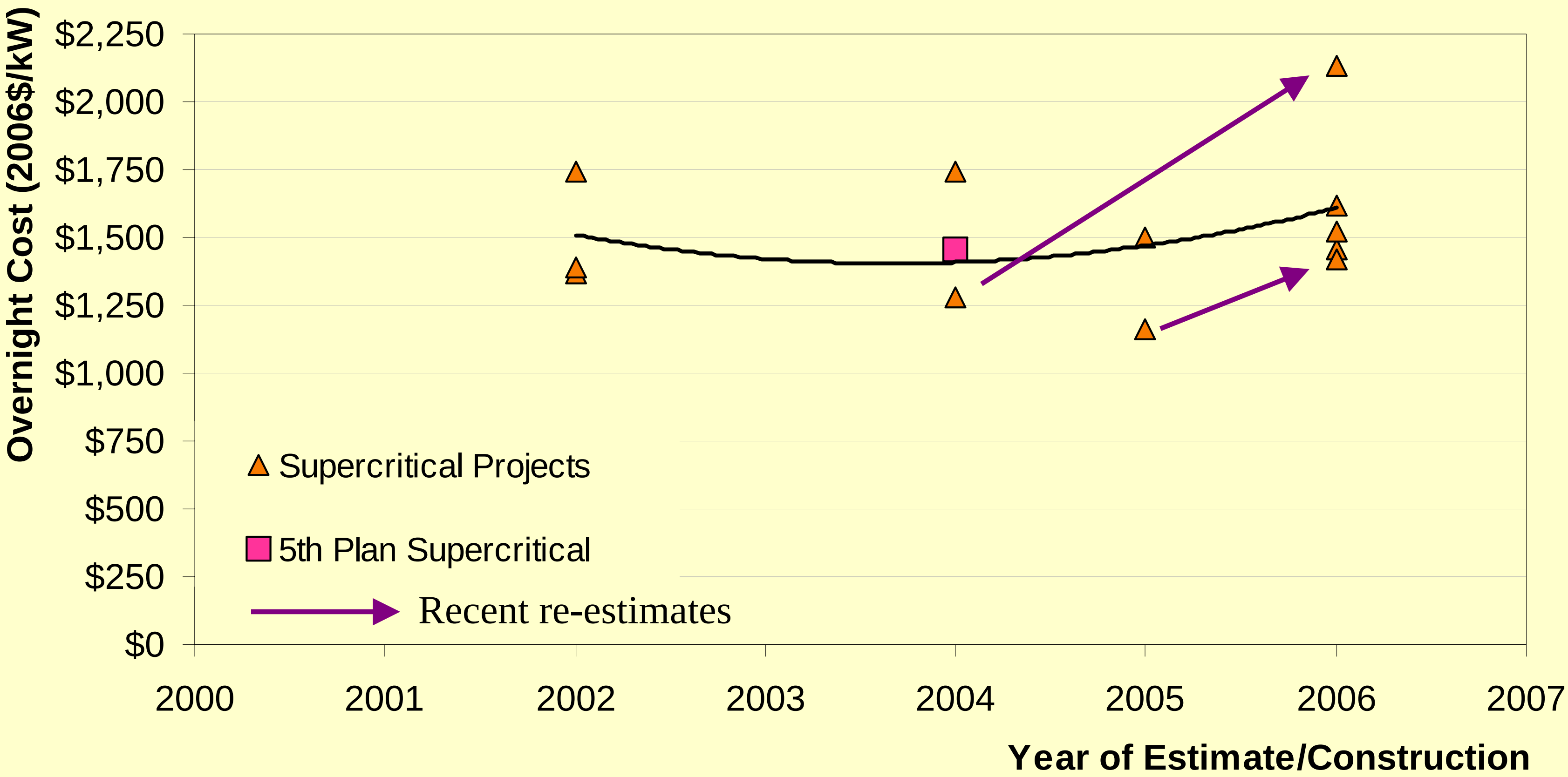
Capital cost: Supercritical steam-electric



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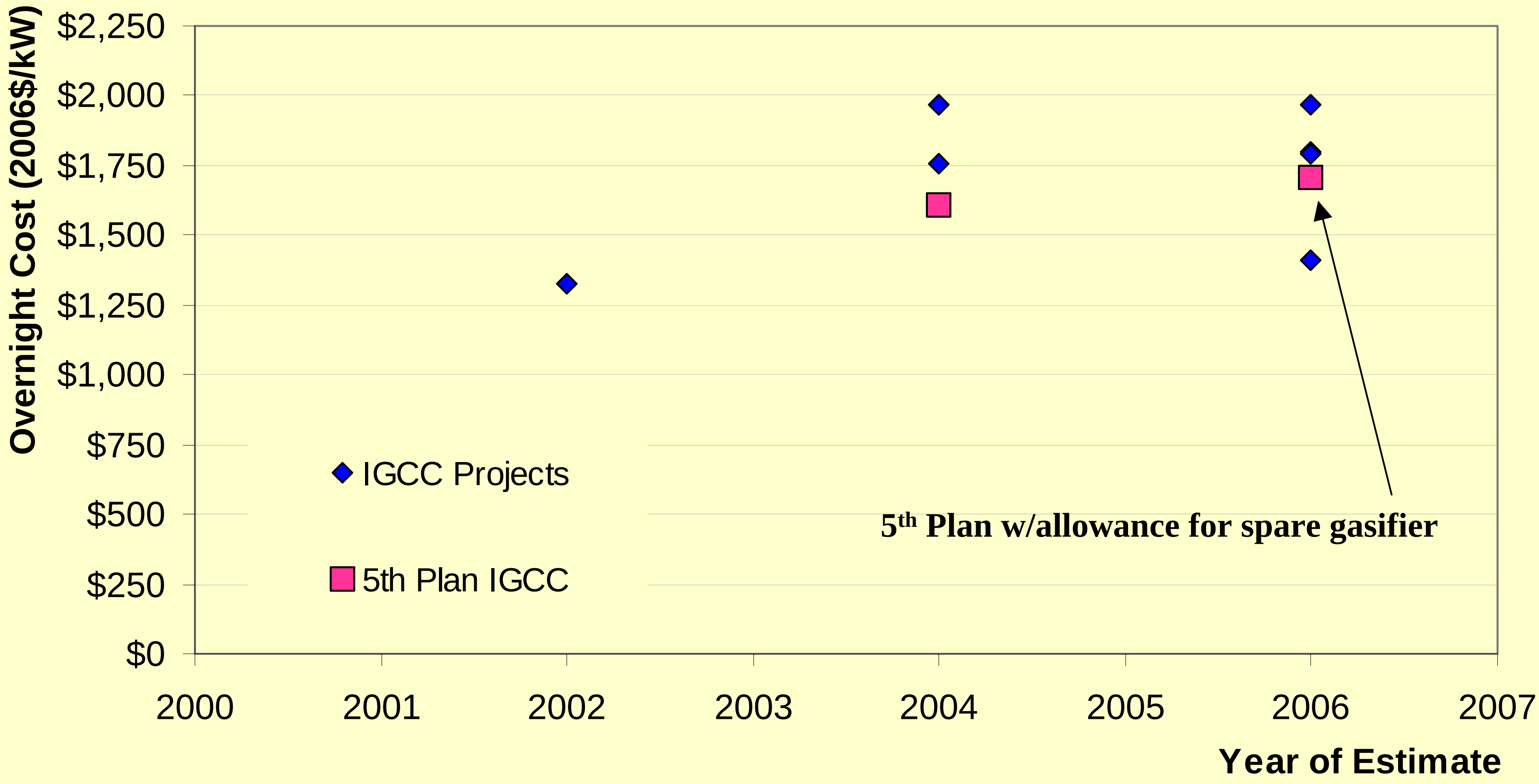
Capital cost: Gasification combined-cycle



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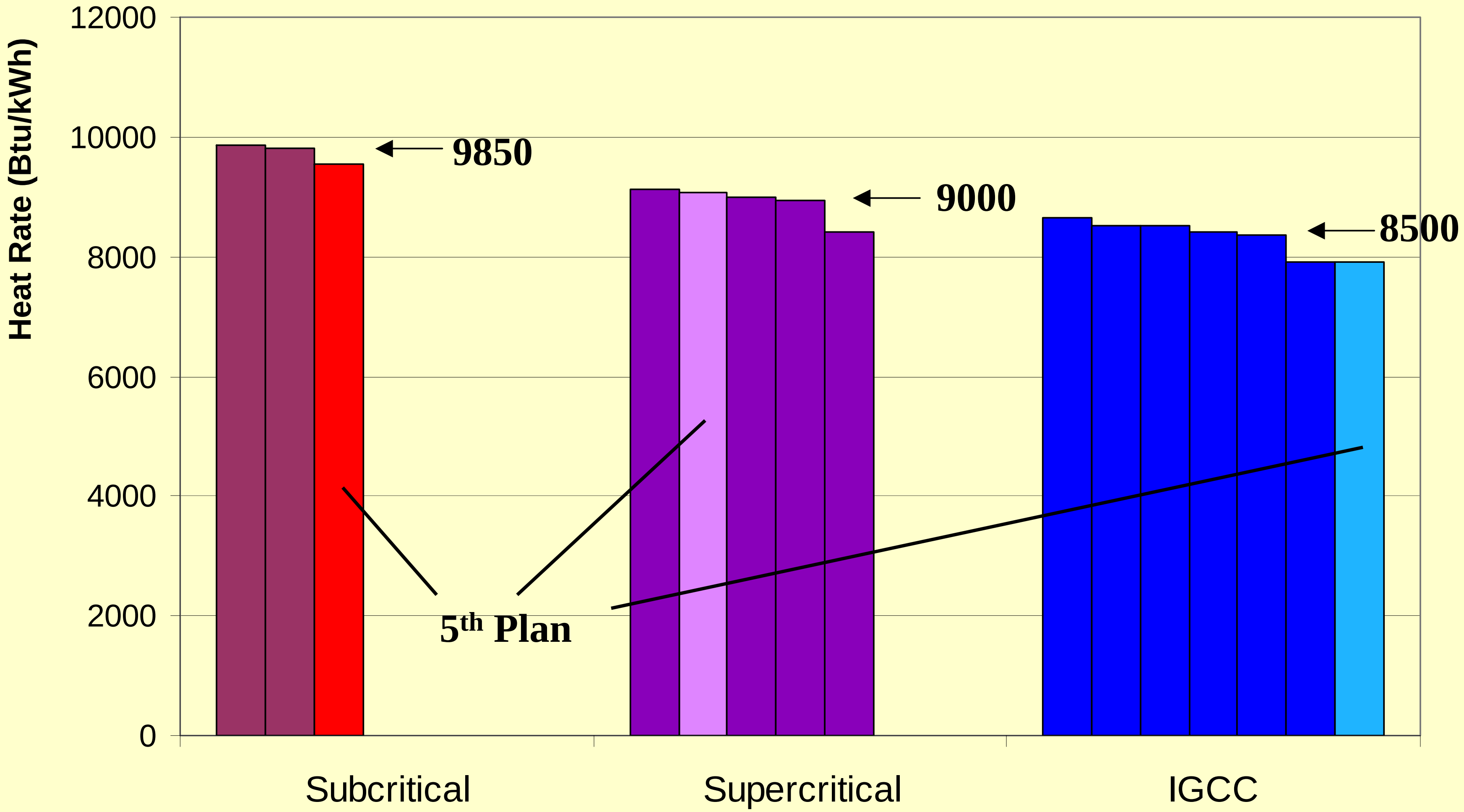
Thermal efficiency



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Big picture conclusions

- Supercritical steam-electric technology entering NA market more rapidly than expected.
- Gasification combined-cycle technology lags SC, but advancing.
- Why Supercritical?
  - Lower cost of power, esp at high elevation
  - Further along the commercialization process
  - Utility, not chemical plant technology
- Why Gasification?
  - Slightly greater efficiency
  - Greater fuel flexibility
  - Superior emission control
  - Lower water consumption
  - Co-production of synthetic fuels
  - Commercial CO_2 separation technology
- Increasing supply of petroleum coke.

Nitty-gritty conclusions

- Increases in the capital costs of all technologies has been observed because of increased commodity cost.
- Plant availability assumptions should be raised from 83/84% to 90%.
- IGCC capital cost should be raised ~ $100/kWh to account for spare gasifier (to achieve 90% availability).
- Efficiency (heat rate) assumptions should be revised:

  Subcritical: 35.7% > 34.6%

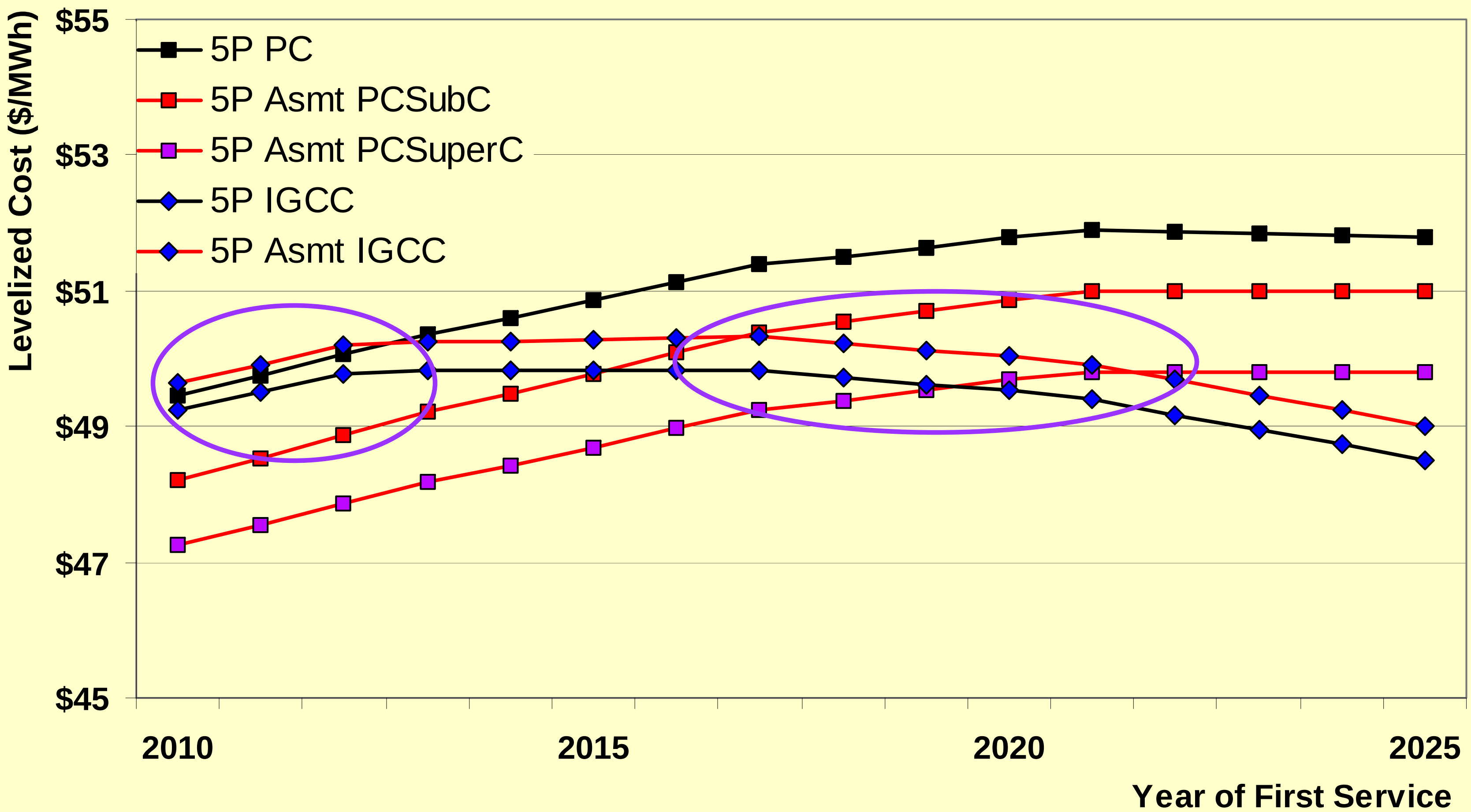
  Supercritical: 37.6% > 37.9%

  IGCC: 43.1% > 40.2%
- "CO2-ready" IGCC plant should be included as option in future plans.

Proposed changes to planning assumptions

	Subcritical	Supercritical	IGCC (w/o CO2 separation)	IGCC (w/CO2 separation)
Capacity (MW)	400	400	425	401
Heat Rate (Btu/kWh)	9550 > 9850	9070 > 9000	7915 > 8500	10,000 > 10,700
Availability	84% > 90%	84% > 90%	83% > 90%	83% > 90%
Cap. Cost (2006$/kW)	$1435	$1457	$1617 > $1708	$2079 > $2161
Earliest Service (greenfield)	2011	2011	2011>2012/13	2011>2012/13

How they stack up – levelized cost basis



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