Dynamic Operability of Coal Plants
燃煤电厂的动态运行能力

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Ken Dragoon
Senior Resource Analyst
Northwest Power and Conservation Council
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- Established by federal legislation to provide regional guidance on energy issues.
  - Council members are appointed by the governors of the four Northwest states: Oregon, Washington, Idaho, and Montana.
- Reviews regional power plan at least every five years.
- Recommends funding for fish and wildlife programs to mitigate effects of hydro power development.
- Encourages broad public participation in regional energy issues.

西北电力与节能委员会

- 由联邦立法成立，为能源问题提供区域性指导。
  - 委员会成员由西北四州（俄勒冈、华盛顿、爱达荷和蒙大拿）的州长任命。
- 至少每5年进行一次地区电力计划审查。
- 提出用于鱼类和野生动物项目的基金建议，以减少水电开发所带来的影响。
- 鼓励公众参与地区能源问题。

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Background

- US coal plants have historically operated as “base load” units--maintaining essentially constant generation levels through time except for planned maintenance and outage events.
- Most power system computer models contained coal plant operating characteristics that had not been carefully examined for a long time.
- With increasing levels of renewable energy, the extent to which coal plants could operate dynamically to balance the system became an important consideration.

背 景

- 美国的燃煤电厂一直都作为“基荷”电源 运行——基本始终维持恒定的发电出力，除非有计划检修或故障事件发生。
- 长期以来，大多数电力系统计算模型中燃煤电厂的运行特性都没有经过仔细校验。
- 随着可再生能源的增加，燃煤电厂在参与系统平衡方面的动态运行能力就成了非常重要的因素。

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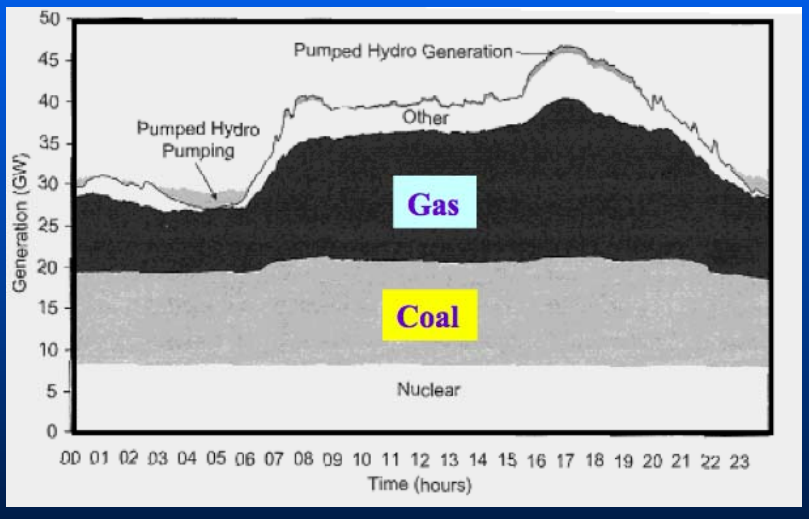
Historical Coal Plant Operation
燃煤电厂过去的运行模式

- Operated at or near full output to the extent possible.
  尽可能地运行在满出力或接近满出力的状态



Adapted from *Renewable Energy in Power Systems*, Ferris and Infield, J Wiley,2008

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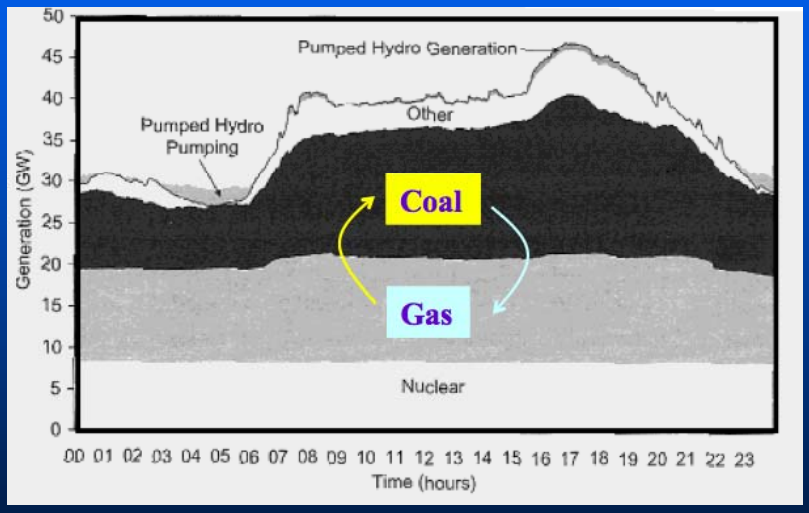
Moving to New Dispatch Order
新的调度规则

- Gas plants have lower emissions, though fuel costs tend to be higher.
  虽然天然气发电的燃料成本高，但其排放量更低。



Adapted from *Renewable Energy in Power Systems*, Ferris and Infield, J Wiley,2008

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Coal and Wind
煤电与风电

- Much of load and wind variability is currently accommodated by natural gas plants (and hydro in Northwest).
  目前，由天然气电厂（和西北部的水电）来平衡大部分的负荷波动和风电出力波动。

- Key questions arise regarding ability of existing system components to contribute to accommodating wind variability.
  存在的关键问题是现有系统元件在应对风电波动方面的能力贡献。

- Can coal plants contribute?
  燃煤电厂能提供一定帮助吗？

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Important Operability Characteristics
重要的运行特性

- Minimum generating capability (% of nameplate MW)
- Maximum rate of output increase (%/minute)
- Maximum rate of output decrease (%/minute)
- Minimum down time (hours)
- Minimum up time (hours)

- 最小发电出力能力 (占铭牌容量的百分比)
- 最大增出力率 (%/分钟)
- 最大减出力率 (%/分钟)
- 最短停机时间(小时)
- 最短开机时间(小时)

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Coal Power Report
煤电报告

- Developed a paper summarizing publicly available studies on ability of coal plants to operate more dynamically:

  Summary Report on Coal Plant Dynamic Performance Capability

  http://rnp.org/sites/default/files/pdfs/RNP%20Coal%20Report%2010Aug16.pdf

- Key question: Can existing coal plants change from base load operation to providing balancing services?
  - Need to assume characteristics for studies of large scale wind integration.

- 发布了一个总结文件，总结对象是分析燃煤电厂更为灵活的动态运行能力的各类公开性研究。

  燃煤电厂动态性能总结报告

  http://rnp.org/sites/default/files/pdfs/RNP%20Coal%20Report%2010Aug16.pdf

- 关键问题：现有的燃煤电厂能是否能够由基荷运行改为提供平衡服务?
  - 在进行大规模风电接入研究时需要对相关特性做一些假设。

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China Shows the Way

- Coal power plants can be specifically designed for dynamic operation.
  - Four 680 MW Castle Peak B units in Hong Kong have operated in a “two-shift” mode for more than twenty years with high reliability.
- What about older units that were not designed for dynamic operation?

中国指出了方向

- 可以对燃煤机组的动态运行能力进行专门设计。
  - 香港青山B厂4台680MW机组已在“两班制” 模式下运行了20多年，且可靠性非常之高。
- 那些设计用于非动态运行的旧机组情况如何呢？

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Basic Challenge: Creep and Fatigue

- Creep is the deformation of power plant components due to temperature and pressure.
  - Base load power plants unavoidably expose components to creep.
- Fatigue is the material response resulting from repeated applications of stress (pressure and temperature).
  - Dynamic operation introduces additional fatigue on system components.
- Components may fail from either creep or fatigue, but the combination of exposure to both significantly accelerates component failure.

基本挑战：蠕变和疲劳

- 蠕变是指电厂各部件因温度和受压而产生的变形。
  - 基荷电厂的各部件会不可避免地发生蠕变。
- 疲劳是指材料对重复性压力作用(压力和温度)的反应。
  - 动态运行会导致更大程度的系统元件疲劳。
- 元件可能因为蠕变或者疲劳而损坏，而这两者的共同作用会加剧元件的损坏。

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Limiting Creep and Fatigue

- The most direct way to limit failures due to creep and fatigue is to operate power plants conservatively.
  - Minimize starts and stops.
  - Limit ramp rates.
  - Operate at constant temperatures and pressures well within design parameters to the extent possible.

降低蠕变和疲劳

- 降低因蠕变和疲劳而造成损坏的最直接方法是电厂保守运行。
  - 最少化开停机次数。
  - 限制爬坡率。
  - 使其尽可能的运行在设计参数范围内和恒温、恒压环境下。

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Coal Plant Design Specifications
燃煤电厂设计规范

- US coal plants 美国的燃煤电厂

Design Ramp Rates

Plant Design	Publication	Ramping Rate	Comments
Sub-Critical	Power-Gen World Wide[12]	5% per minute	From 50% to 100% Capacity
Sub-Critical	IMTE AG Power Consulting[13]	3-5%	
Super-Critical	Babcock Power[14]	7% per minute	Typical from 50-90% Capacity
Super-Critical	Power-Gen World Wide[9]	7-8% per minute	From 50% to 100% Capacity
Super-Critical	IMTE AG Power Consulting[10]	7-8% per minute	

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Coal Plant Operation
燃煤电厂的运行

- Operators tend to keep well within specifications.
  操作员完全遵守规范要求

1982 EPRI Survey Results

Capacity (MW)	Design	Avg. Ramp Rate (% / min)	Max Ramp Rate (% / min)
180	Sub-Critical	1.8	3.6
300	Sub-Critical	2.0	3.1
420	Sub-Critical	1.1	2.9
540	Sub-Critical	1.7	2.8
660	Sub-Critical	1.3	3.7
420	Super-Critical	1.3	4.3
540	Super-Critical	1.1	3.6
660	Super-Critical	1.2	2.0
780	Super-Critical	0.9	3.5
900	Super-Critical	1.0	2.0

Keys to Dynamic Operation
动态运行的关键

- Implement design and operation changes that minimize changes in temperature and pressure on important components over changes in output levels.
  改变设计方法和运行模式，从而使重要元件感受到的温度变化和压力变化最小化，而非出力水平变化最小化。

- Feasible design changes are limited by high costs of replacing or changing major components (e.g., boilers)
  由于主要部件（如锅炉）的替换或改造成本非常高，可行的设计改造手段很有限。

- Common to these efforts are expanded control and instrumentation.
  更为常用的方法是扩展控制和仪表使用。

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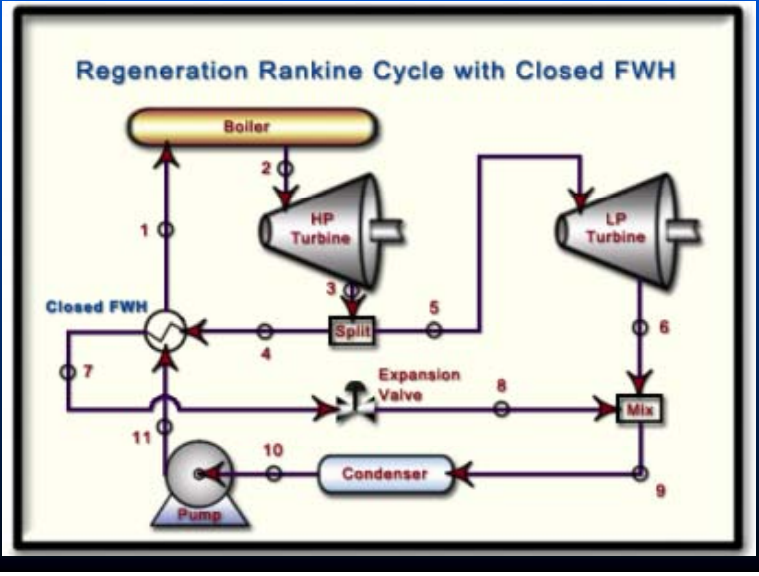
Basic Coal Plant Design
燃煤电厂的基本设计

- Older coal plants tend to be sub-critical drum boiler designs and run in“constant pressure operation” mode.
  老式燃煤电厂通常采用亚临界汽包锅炉设计，并且在“常压运行”模式下运行。



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Constant Pressure Operation (CPO)

- CPO is standard operation for baseload operation.
  - Throttling valve between boiler and high pressure turbine inlet maintains constant pressure.
    - » Pressures and temperatures are higher on the boiler side.
  - Changes in output can be achieved by opening or closing the throttling valve.

常压运行 (CPO)

- CPO是基荷运行的标准运行方式。
  - 锅炉和高压汽轮机之间的节流阀维持恒压。
    - » 锅炉侧的压力和温度相对更高。
  - 可以通过节流阀的开关来改变出力。

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Disadvantages

- Opening the throttling valve increases temperature and pressure to the turbine blades.
  - Contributes to fatigue
  - Reduces pressure in boiler requiring disproportional increase in fuel feed and reducing efficiency.
  - Throttling valves not normally designed for dynamic operation and begin to fail more often.

不足之处

- 打开节流阀会提高汽轮机叶片的温度和压力
  - 增加疲劳
  - 需要非比例地增加燃料输入才能降低锅炉的压力，且会导致效率降低。
  - 节流阀通常不是为动态运行而设计的，会导致更为经常性的损坏。

Variable Pressure Operation (VPO)

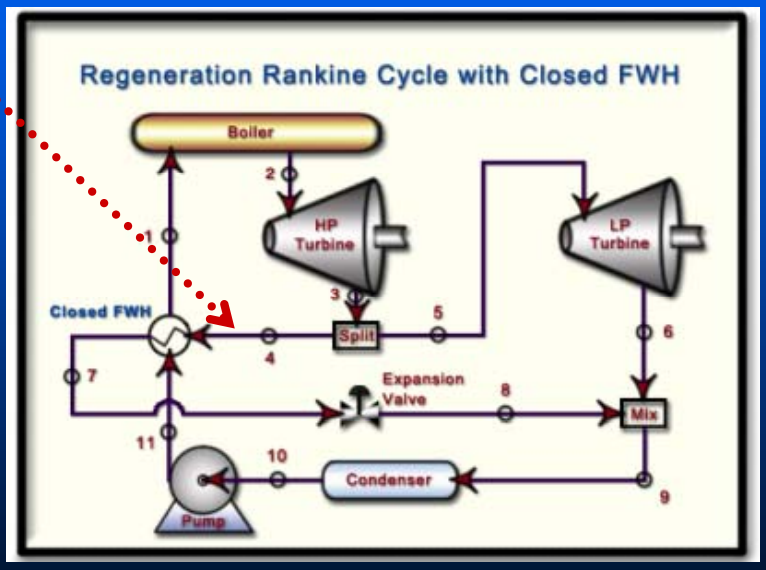
- Leaves throttling valve open.
  - Minimizes temperature and pressure differences between turbine and boiler.
- Controls output by adjusting firing rate.
  - Introduces control complexity.
- Allows more dynamic operation while minimizing wear on turbines.
- Hybrid Operation leaves throttling valve nearly open, but adjustable over a narrow range.

变压运行(VPO)

- 打开节流阀
  - 使汽轮机和锅炉的温度差异和压力差异最小。
- 通过调整燃料填充速率来控制出力
  - 增加了控制的复杂性
- 允许更为动态的运行，同时保证汽轮机的磨损最小。
- 混合运行使得节流阀几乎打开，但能够很小的范围内进行调节。

Pre-Heater Bypass Control
预热器旁路控制

- Steam at the low pressure ends of the turbines is normally routed through the feed-water heat exchanger to pre-heat water entering the boiler to boost efficiency.
- 汽轮机低压端的蒸汽通过给水换热器流到预热器，再进入锅炉以提高效率。
- Turbine output can be increased by limiting or eliminating flow to the feed-water heater.
- 通过限制或者停止向给水加热器供汽可以提高汽轮机的出力
  - Reduces overall efficiency of generation but increases output without increasing pressure or temperature at the turbine.
  - 降低了发电机的整体效率，但是在没有增加汽轮机压力和温度的情况下提高了出力。
  - Controls over minutes versus seconds for throttling, hence the merit of hybrid operation
  - 分钟级和秒级的节流控制 正是混合控制的优点。



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Other Strategies
其他策略

- Steam output can be increased by positioning the boiler fireball lower over the evaporator.
  将锅炉火球置于比蒸发器更低的位置可以提高蒸汽输出
  - Reduces efficiency, not all power plants have tilting burners.
    降低了效率，并非所有的发电厂都有倾斜式燃烧器。
- Adjust grinding mill pressure.
  调整磨煤机压力
  - The coal mill itself represents storage capability that can be accessed by raising or lowering mill pressure.
    通过增加或者降低碾磨压力可以使磨煤机自身实现其储能能力。

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Need for Control and Instrumentation

控制和仪表需求

- These strategies need to act together for optimal results.
- Proper instrumentation and automated controls (in some cases manual controls) are needed to optimize dynamic response while minimizing temperature and pressure transients during operation.
  - Likely requires some experimentation.
- In at least one case, more and better C&I increased ramp rate three-fold while actually improving heat rate and reducing emissions.

- 为了获得最优结果，这些策略需要协同作用。
- 需要合适的仪表和自动化控制(某些情况下是手动控制)来优化动态响应，同时实现运行中温度和压力暂变的最小化。
  - 可能需要一些试验。
- 至少在一种情况下，更多、更好的控制和仪表能增加3倍的爬坡率，同时改善热耗率、降低排放。

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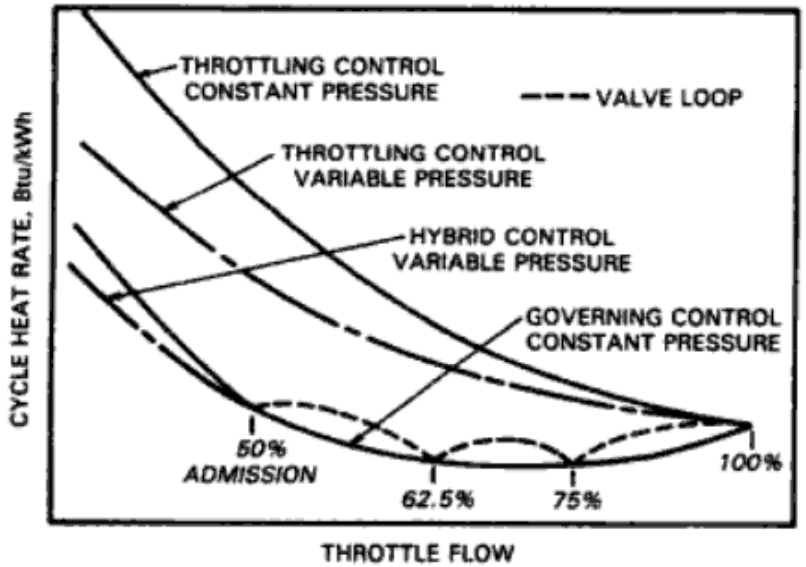
Effects on Heat Rate

对热耗率的影响

- Dynamic operation tends to increase heat rate (less efficient).
  动态运行趋于增加热耗率(降低效率)。
- More complex control schemes can be optimized to reduce the effect.
  通过对更为复杂的控制方案进行最优组合，可以减小这种不利影响。



Source: *Power plant engineering*, Drbal, Boston, Westra, Black & Veatch 1995

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Minimum Generation
最低发电水平

- Defined as the lowest level of safe and reliable plant operation without need for supplemental firing.
  - Typically 35-40% of nameplate capability.
- Especially important parameter in accommodating high levels of wind generation during light load hours.
- Operation at low levels characterized by high heat rates, poor power control, poor emission control performance.

- 被定义为电厂在不需要补充火力情况下的最低安全、可靠运行水平。
  - 通常是铭牌容量的35%-40%。
- 该参数对于在小负荷时段消纳高风电出力尤其具有重要意义。
- 低出力运行的表现是热耗率高、功率控制差、排放控制差。

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Reducing Minimum Generation Levels
降低最低发电水平

- Combinations of adjustments to unit master control, feed-water and boiler control, and turbine retrofits can reduce minimum generation levels.

  发电机主控制、给水和锅炉控制以及汽轮机改造的组合，可以降低最低发电水平。

Example Improvements in Minimum Load Retrofits

Size (MW)	Current Minimum Load	Potential Minimum Load
254	35%	24%
267	34%	22%
65	23%	8%
446	28%	22%
258	52%	35%
880	40%	28%
524	46%	38%
70	43%	21%

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Minimum Run and Down Time
最短开停机时间

- Coal plants typically take 12 hours to cold start (< 200C), 4 hours to warm start (>200C), and 1 hour to hot start (>400C).
  燃煤电厂冷启动通常需要12小时(<200C)，温启动需要4小时(>200C)，热启动需要1小时(>400C)。

- Turbine bypass systems allow steam to circulate around and through the turbines to maintain temperatures without loading the turbine.
  在不带动汽轮机的情况下，汽轮机旁路系统允许蒸汽在汽轮机内循环以保持温度。

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Dynamic Operation Raises Failure Rates and Costs
动态运行增加了故障率和成本

- Although dynamic operation introduces additional stresses on power plant components, cost effective means exist to limit these effects through more sophisticated control and instrumentation techniques, augmented by selected retrofits.
- There is no one answer for all power plants.
  - *There is only one way to improve the dynamic performance of fossil fired power plants: Hard work carried out by control engineers… it is my experience that each power plant is acting different…* (European power plant engineer responding to our inquiries)

- 虽然动态运行给发电厂元件带来了额外的压力，但是可以寻求性价比高的方法，通过成熟的控制技术和仪表技术来弱化这些影响，并可以通过特定的改造来增强这种弱化效果。
- 对于所有电厂没有统一的答案。
  - *提高化石燃料电厂动态特性的方法只有一个：控制工程师的努力工作…这是我的经验，每个电厂的情况是不同的*(欧洲的电厂工程师会对我们的调查进行反馈)

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Coal Plants Can Contribute to System Balancing
燃煤电厂能够参与系统平衡

- There will be costs.
  - Power plant C&I and appropriate retrofits.
  - Higher O&M costs.
  - Higher outage rates.
  - Higher heat rates.
- As the importance of emissions continues to increase, planners and engineers must seriously consider the tradeoffs.

- 会产生如下成本：
  - 电厂控制和仪表设备以及适当的改造
  - 较高的运行维护费用
  - 较高的故障率
  - 较高的热耗率
- 由于排放量的重要性日益增加，规划人员和工程师必须认真权衡。

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Thank You!

谢　谢！

- Please feel free to contact me with questions.

如有问题，可以与我联系

– Kdragoon@nwcouncil.org

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