The Value of Flexible Generation

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Introduction

Power systems have always required flexibility to respond to variations in aggregate net load. Some of the variability, such as the daily, weekly and seasonal load cycles is predictable. Other variability, such as the sudden failure of a generator or transmission line is not. Wind and solar generation add variability and uncertainty with characteristics that are both similar to and different than those the system dealt with in the past.

Variability and uncertainty span a time range from cycles (the failure of a large generator) to seasons (the annual load cycle). Events differ in their frequency as well with large contingencies being relatively infrequent (every few days) but small fluctuations in aggregate load (regulation) being continuous. Wind and solar have the largest impact on large but infrequent and non-periodic ramps. These ramps may be predictable with improved short term weather forecasts. They are similar to conventional contingencies in their frequency and magnitude but differ in that they are much slower to unfold.[1]

Since generation and load must be balanced instantaneously and continuously to keep the power system stable and operating, controllable reserves must be available to respond to variations in load and supply. From a reliability perspective it does not matter if these reserves are generation, demand response, or storage as long as they respond with the speed, accuracy, and magnitude that is required. The different characteristics in event magnitude, speed, and frequency have important economic consequences for the resources that supply the response, however. It is this flexibility on the part of the power system to be able to utilize a range of resources, and the difference among resources in the cost of supplying response, that couples the technical reliability response requirements to the economic optimization of supply. A series of cooptimized energy and ancillary service markets have proven to be an effective way to find the lowest cost resource mix to reliably serve load each hour. Maximizing a generator's flexibility gives it the greatest opportunity to maximize its own profitability by shifting to supply the response the power system values most at any point in time.

Generator Flexibility

As will be discussed, the power system quantifies its flexibility requirements in terms of energy and ancillary service market products. In regions without organized markets flexibility requirements are quantified through security constrained unit commitment and security constrained economic dispatch (SCUC/SCED) scheduling of energy and ancillary services with, hopefully, similar results. Ideally these services are defined in a technology neutral way based

[1] While individual wind turbines and solar panels exhibit rapid shifts in output the output of a large wind or solar fleet ramps much more slowly due to the geographic dispersion.

on the power system's functional requirements. Any resource that can meet the functional requirements is encouraged to offer their services.

The flexibility of greatest interest here is in the control of real power (reactive power can be of interest as well for voltage control). The characteristics of concern include the range of control (MW), minimum load, ramping speed (MW/min), response accuracy, advanced notification required, and the response duration. Costs associated with each of these characteristics, including efficiency at minimum load, are very important as well.

The reason some characteristics are important is obvious. For example, the ramp rate limits how much response (MW) can be obtained within five or ten minutes and limits the amount of reserves that a generator can sell. Other characteristics may not be as obvious. Minimum load is important because it limits the range of response that can be offered with the control range being equal to the maximum load minus the minimum load (subject to the ramp rate constraint). But minimum load is also important because it determines the cost of being in the reserve market at all. As we will see, it may be profitable for a generator to sell spinning reserve even if the generator must take a loss on the energy production. Profitability depends on how much money the generator looses while operating at minimum load versus the amount it is paid for the reserve it is supplying. The energy market loss depends on both the market clearing price for energy versus the generator's fuel price and minimum load efficiency but it also depends on the minimum load MW amount. Reducing the minimum load reduces the energy market losses while also increasing the reserve range.

Reducing the time and cost for bringing a unit on line is important for profitability as well. It enables the generator to move between energy and ancillary service markets rapidly as prices shift. A unit that can come on line and load within ten minutes can also sell non-spinning reserve. One that takes 24 hours to come on line has a difficult time fully participating in the energy markets without risking losses for overnight operations and when conditions change.

Response duration is typically not a problem for generators though it is for both storage and demand response. Emissions limited generators can have response time limitations in which case they must carefully monitor which services they offer.

An ideal generator has a very low minimum load, high efficiency throughout the operating range, and fast and accurate ramping capability. It will be equipped with a responsive governor and be on automatic generation control (AGC).

Energy Markets

ISOs and RTOs, which serve about two thirds of the load in North America, operate day-ahead hourly, hour-ahead hourly, and five-minute energy markets. These energy markets allow for the optimal scheduling of generation to meet load. They deal with variability and uncertainty by providing changing price signals that reflect the value of energy with prices rising when additional generation is required and prices falling (and sometimes going negative) when generation should be reduced. Generators that are able to quickly and accurately respond to these price signals can profit more than inflexible generators.

Day-ahead markets (and day-ahead scheduling in non-market areas) can deal with the normal daily, weekly and seasonal load pattern and can accommodate a significant amount of the load variation driven by weather with current forecasts. Figure 1 shows these day-ahead hourly energy prices patterns for the NYISO for 2012 but it shows random volatility and price spikes as well.

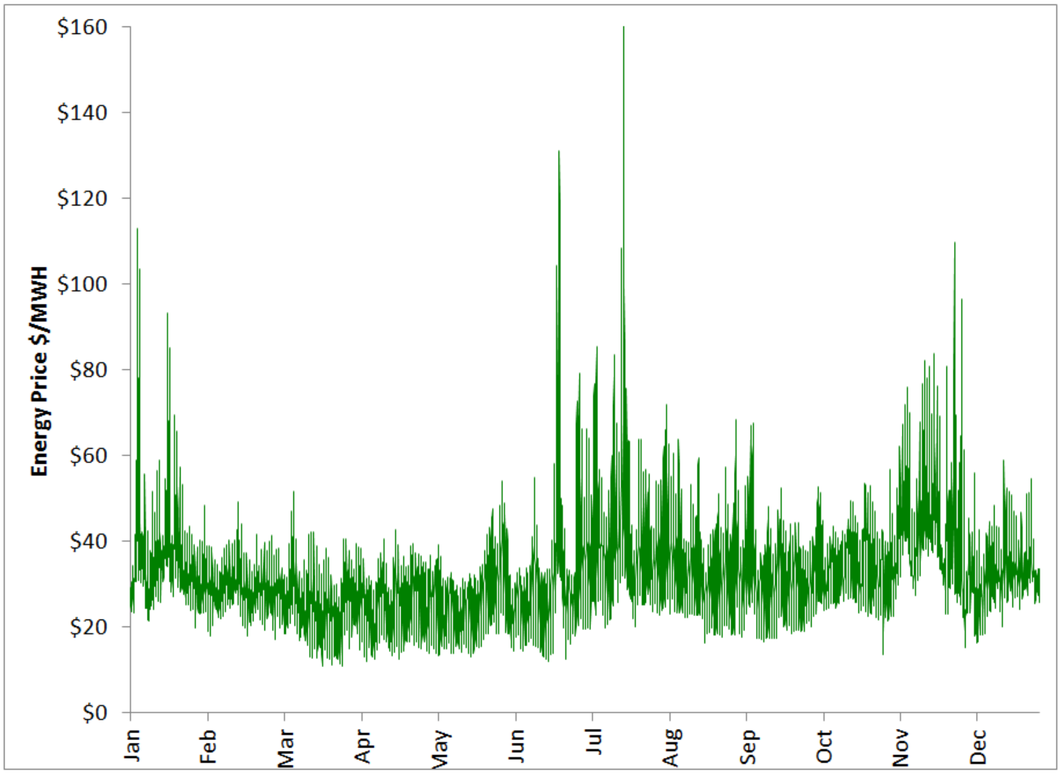

Figure 1 NYISO day-ahead reference bus hourly energy prices for 2012 show daily, weekly and seasonal patterns along with random volatility.

Day-ahead markets clear, as their name implies, the day before actual operations. Generators (and loads) submit their availabilities and prices (by 5am for NYISO) and the system operator clears the market for each hour of the next day (by 11am for NYISO), notifying each generator of the hourly price and its commitment to supply (Figure 2). The hour-ahead market provides an opportunity to adjust the generation production schedules based on changed conditions. A generator may have a maintenance problem that forces it off or the load may be higher or lower than expected due to changed weather. The forecast wind and solar output will almost certainly be different than what was expected the day before. Generators again offer their unscheduled capability (75 minutes before the hour for NYISO) and the system operator again clears the market (30 minutes before the hour for NYISO). A final market is run for each 5 minute operating interval, typically requiring offers ten minutes before the start of the interval, market clearing and communications by five minutes prior to the interval, and a five minute ramp into the operating interval. The hour-ahead and five-minute markets allow both the generators to true up their positions and the system operator to refine the balancing of generation and load. The market volume is greatest day-ahead with lesser market volumes hour-ahead and for the five-minute market.

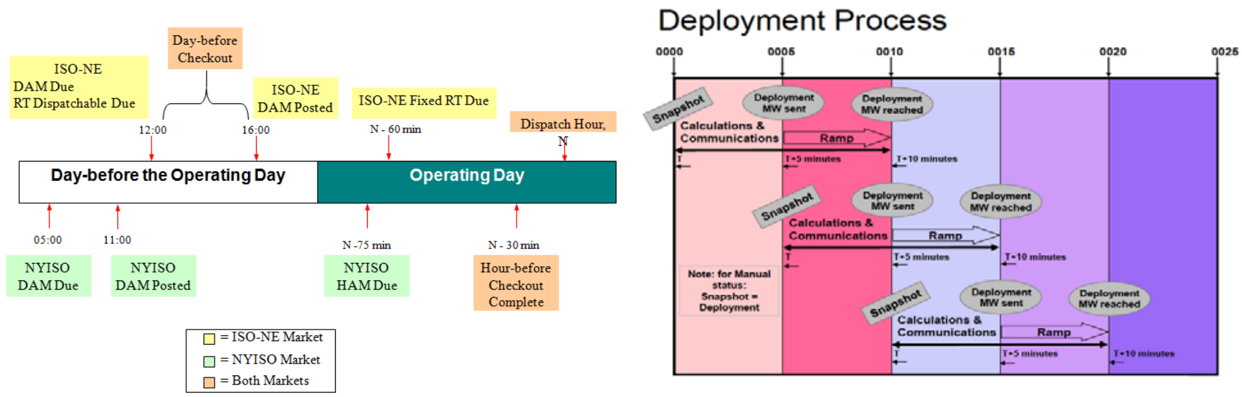

Figure 2 Typical market clearing processes for day-ahead and hour-ahead (left) and five minute markets (right).

Interestingly, Table 1 shows that while there is typically a significant difference between the day-ahead, hour-ahead, and five minute price for any particular interval (there would be no need for the markets if this were not the case) the annual average prices for all three markets are typically quite close: $31.94/MWH day-ahead, $31.33/MWH hour-ahead, and $31.66/MWH five-minute for NYISO in 2012. This means that unlike purchasing expensive ancillary services, on average, the system operator obtains the flexibility of adjusting schedules hour-ahead and every five minutes at no significant cost. The generators find it in their own profit-maximizing self interest to respond to the changing hour-ahead and five-minute price signals and flexible generators have a greater chance to profit from energy price volatility.

Table 1 While 2012 NYISO annual average energy prices from all three markets are very close (upper) the average difference between market prices for each interval were quite high (lower).

$/MWH	Day-Ahead	Hour-Ahead	5-Minute
Annual Average Energy Price	$31.94	$31.33	$31.66
	Day-Ahead vs Hour-Ahead	Day-Ahead vs 5-Minute	Hour-Ahead vs 5-Minute
Average |Δ| Energy Price Each Hour	$36.08	$39.43	$30.58

Figure 3 shows that even on an annual average basis the five-minute and hour-ahead prices are more volatile than the day-ahead NYISO prices. Figure 3 also shows that the system operator utilizes the five minute market to help compensate for the scheduled day-ahead transitions that occur at the top of each hour. On average, five-minute prices spike in one direction and then in the other at the top of each hour, depending on if the system is ramping up or down. Similarly, the system operator appears to use the fifteen minute hour-ahead scheduling intervals to help with system ramping. Figure 4 shows the higher volatility of the five-minute and hour-ahead prices for an example day.

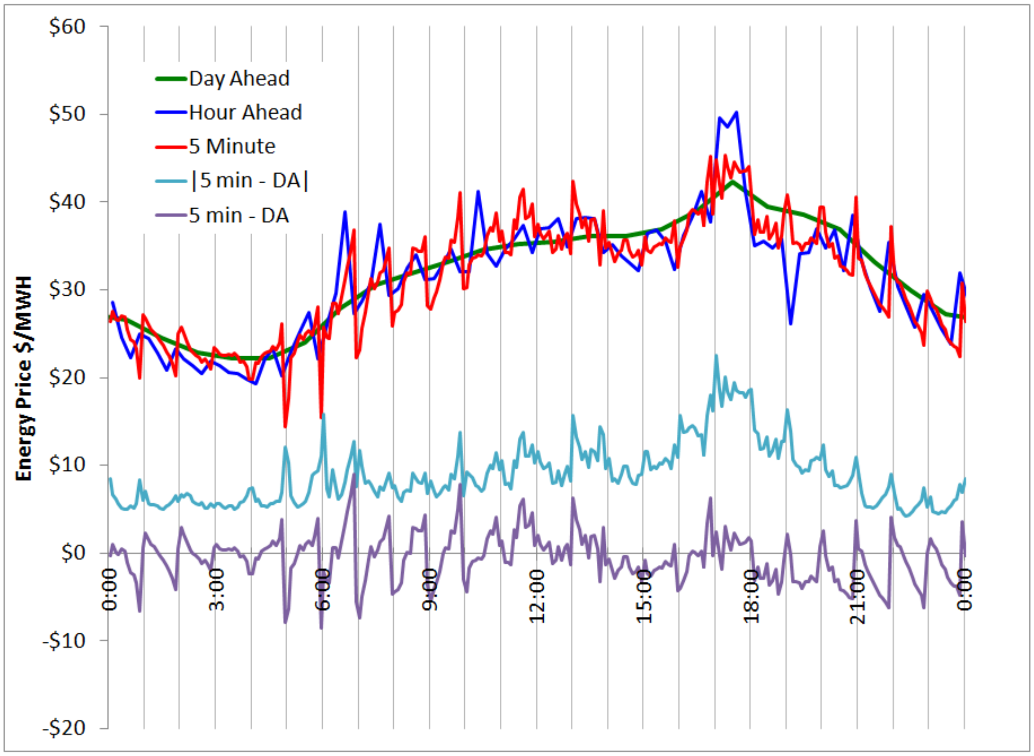

Figure 3 Average 2012 daily five-minute and hour-ahead prices are more volatile than the day-ahead price pattern.

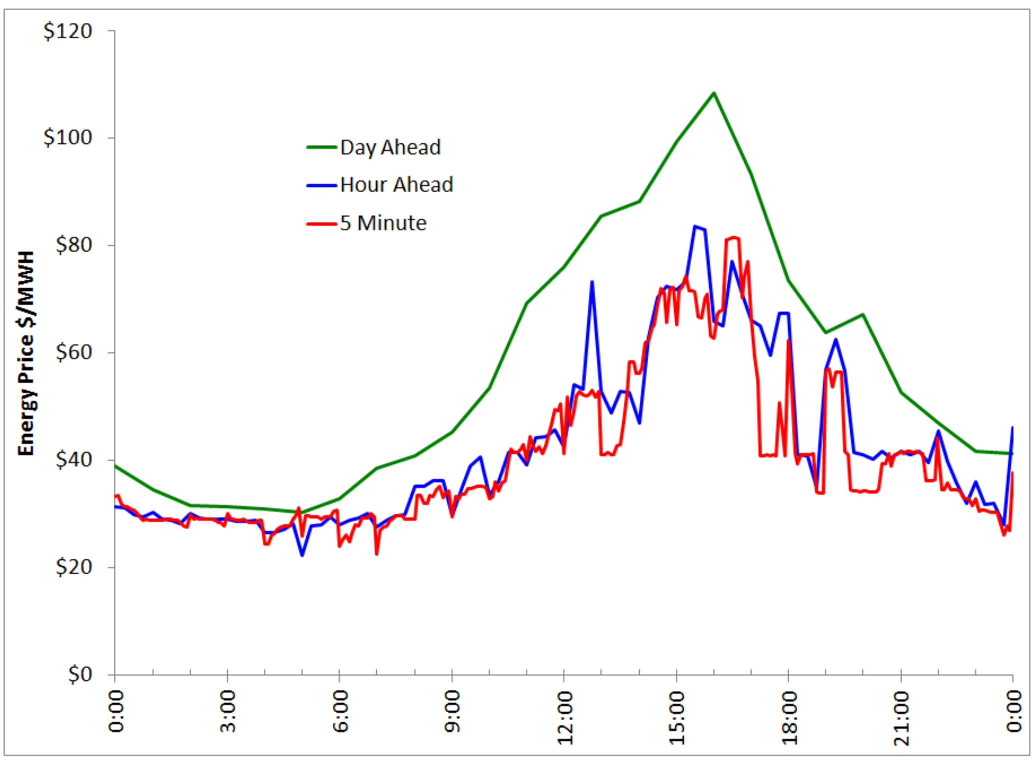

Figure 4 Five minute and hour-ahead prices were more volatile than day-ahead prices on July 16, 2012 for the NYISO.

Price duration curves (Figure 5) show that all three markets have similar patterns of thousands of hours in the $20/MWH to $50/MWH range. This does not mean that the prices were the same in all three markets for any specific interval, only that the duration patterns are similar. The tails of the curves show that for a few hundred hours the hour-ahead and five-minute markets have larger price excursions, both up and down. A generator that is able to rapidly respond to these high prices by generating and the low or negative prices by reducing output or turning off will increase its profits.

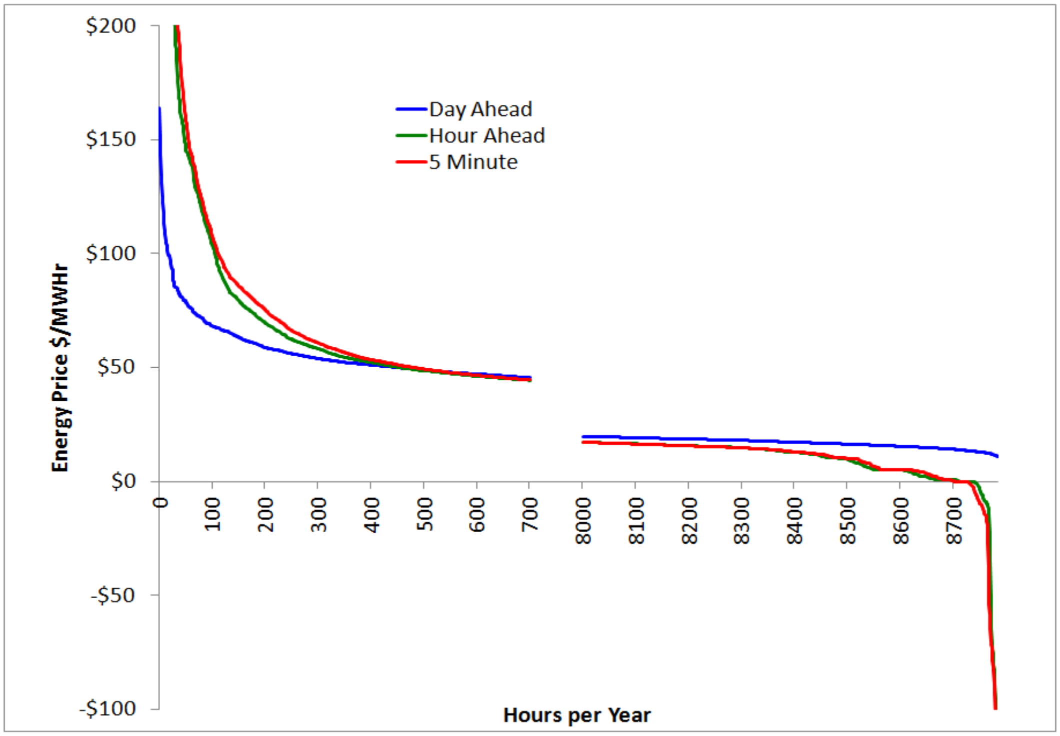

Figure 5 The higher volatility of the five-minute and hour-ahead prices is shown by the price duration curves for NYISO 2012.

Price duration curves are useful for understanding how often prices spike but they loose the simultaneous linkage between the markets. While the patterns shown in Figure 5 are very similar for all three markets, on average there was a $36.08/MWH difference between the day-ahead and hour-ahead prices in each interval, a $39.43/MWH difference between the five-minute and day-ahead prices, and a $30.58/MWH difference between the five-minute and hour-ahead prices (Table 1). Figure 6 provides duration curves for these price *differences*.

Interestingly there is quite a bit of volatility in the five-minute prices themselves. This can be partially seen in Figure 3. Figure 7 presents a price duration curve showing that the maximum five-minute price exceeded the minimum price by more than $11.50/MWH during 3000 hours of 2012 and $30/MWH for 1000 hours. NYISO settles on the five minute prices (a practice that other ISOs will likely eventually adopt) so a very flexible generator may be able to profit by rapidly responding to the five-minute prices.

A generator with a lower minimum load, faster ramping, high efficiency at low load, faster and lower cost off/on/off cycling can respond better to changing prices and profit from the volatility of the faster markets. A generator does not care about energy price volatility when the energy price is either continuously above or below the generator's marginal operating cost. If the energy price is higher the generator should operate, any price above marginal costs is profit. Similarly, if the energy price is below the generator's marginal operating cost it should not be running. The difficulty comes when energy prices move or if the generator is constrained. Most generators could not turn off for an interval or two if the five-minute price dropped below the marginal operating cost. The generator would be better off riding through the price drop, suffer some loses, and continue to profit when the price rises again. If this happens too often or if the price drop is long enough then it is better for the generator to cycle off. In any event, the generator should minimize output during the unprofitable intervals.

Avoiding the faster markets is not necessary or wise. With annual average prices being essentially equal it might appear to be better for a generator to only participate in the day-ahead market. The generator is then guaranteed a profit in each hour it is selected. But if the hour-ahead or five-minute price drops the generator might be better off reducing its output and meeting its day-ahead commitment from the faster market, increasing its profit. Similarly, a generator might elect to withhold some of its output from the day-ahead market if there is reason to think that the hour-ahead or five-minute market will offer a higher price during a particular interval.

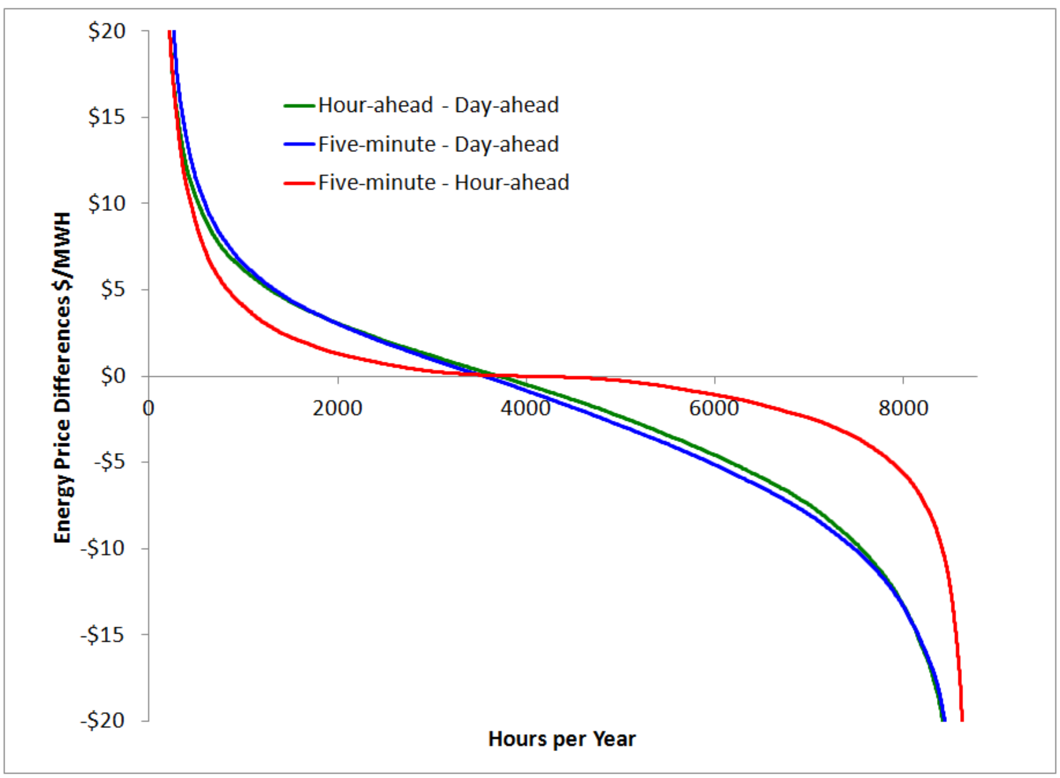

Figure 6 Prices were frequently different between the three NYISO markets in 2012.

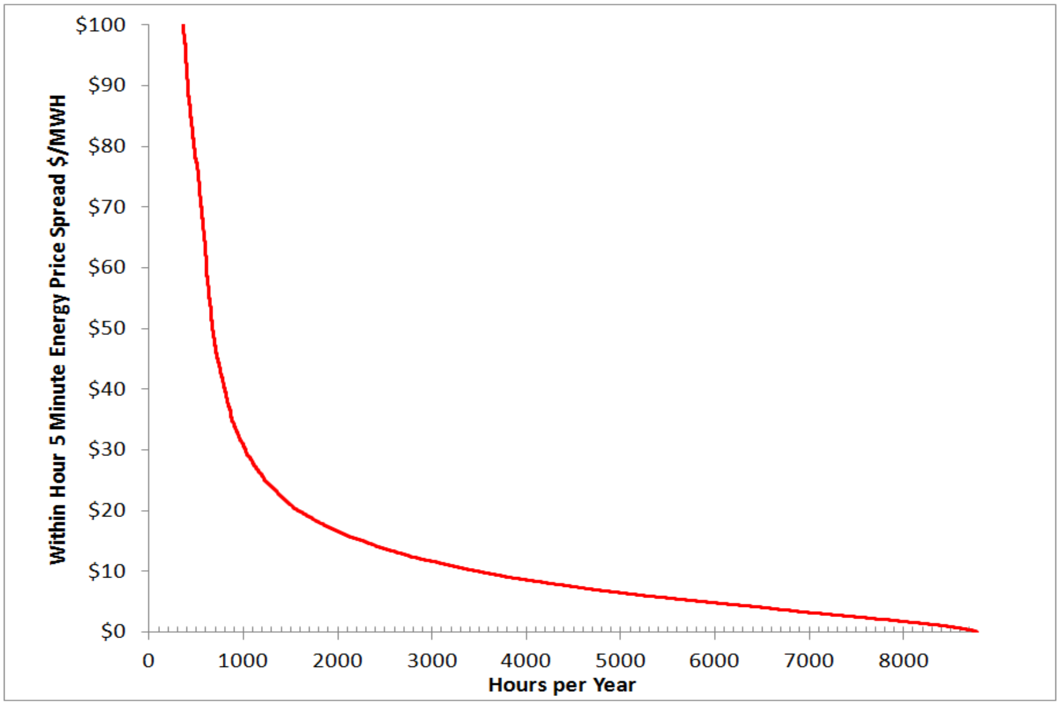

Figure 7 Within-hour price differences were significant for many hours in the five-minute market for NYISO 2012.

Ancillary Services

System operators procure and use a series of ancillary services to compensate for energy imbalances that occur faster than energy markets (or economic scheduling of generation in non market areas) can react to (Figure 8). Regulation and following (following is not yet a commercial service in most locations) are used continuously under normal conditions (Figure 9) while spinning reserve, non-spinning reserve, and supplemental operating reserve compensate for large contingencies (Figure 10). ISOs and RTOs procure ancillary services through markets that are cooptimized with their energy markets. Dedicated capacity is reserved to provide each ancillary service and the primary cost is the opportunity cost of withholding that capacity from the energy market.

Inertia

Inertia is the inherent response a synchronous generator (or motor) provides to the power system when there is a major disturbance. Response is based on the rotational mass of the generator and it slows the frequency decline, giving time for governors and AGC to respond. It is not a paid ancillary service and may not become one. Appropriately designed inverter connected wind plants can provide synthetic inertia.

Governor/Frequency Response

Governor response or frequency response is the autonomous controlled response provided through generator governor action that increases output as frequency declines and decreases output when frequency rises. It is not yet a paid ancillary service but it may become one. Some generators incur an efficiency penalty when they operate with their throttling valves positioned such that their governors can effectively respond to frequency deviations.

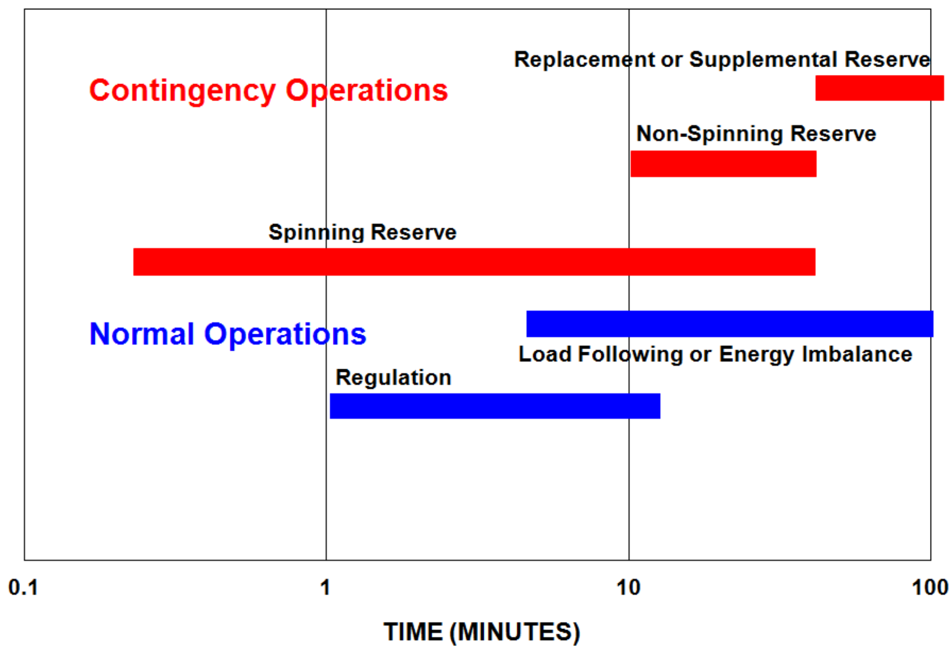

Figure 8 Ancillary services are differentiated by time frame and frequency of use.

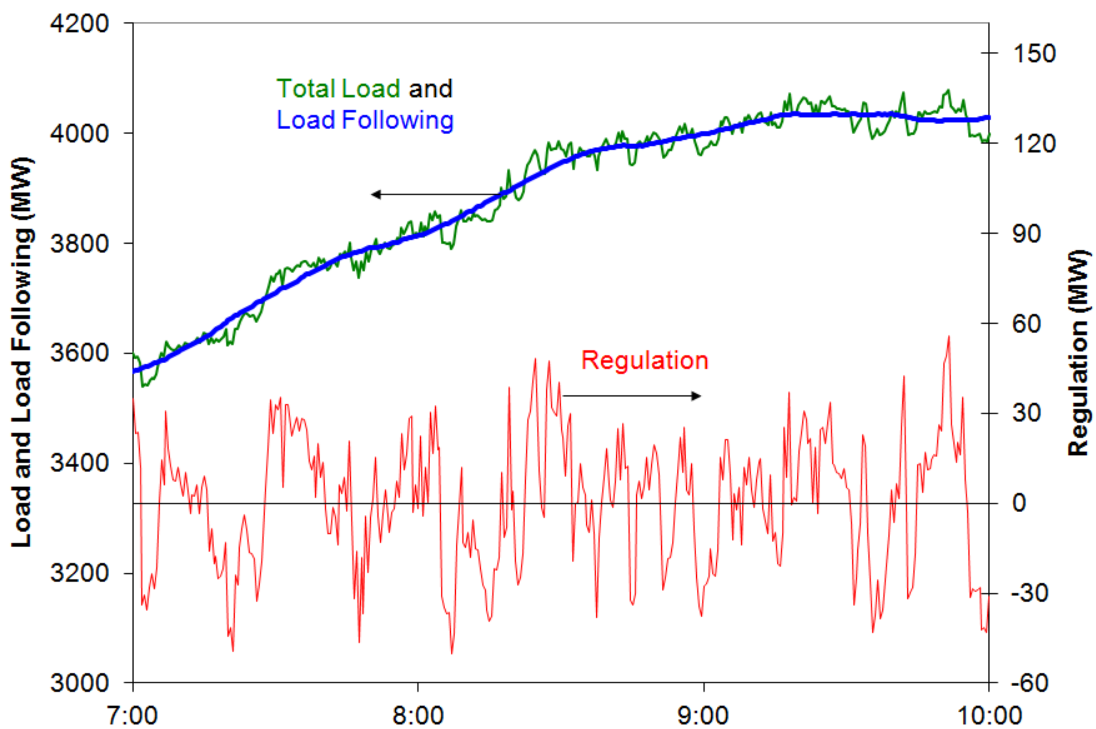

Figure 9 Regulation responds to minute-to-minute random variability while following responds to longer ramps.

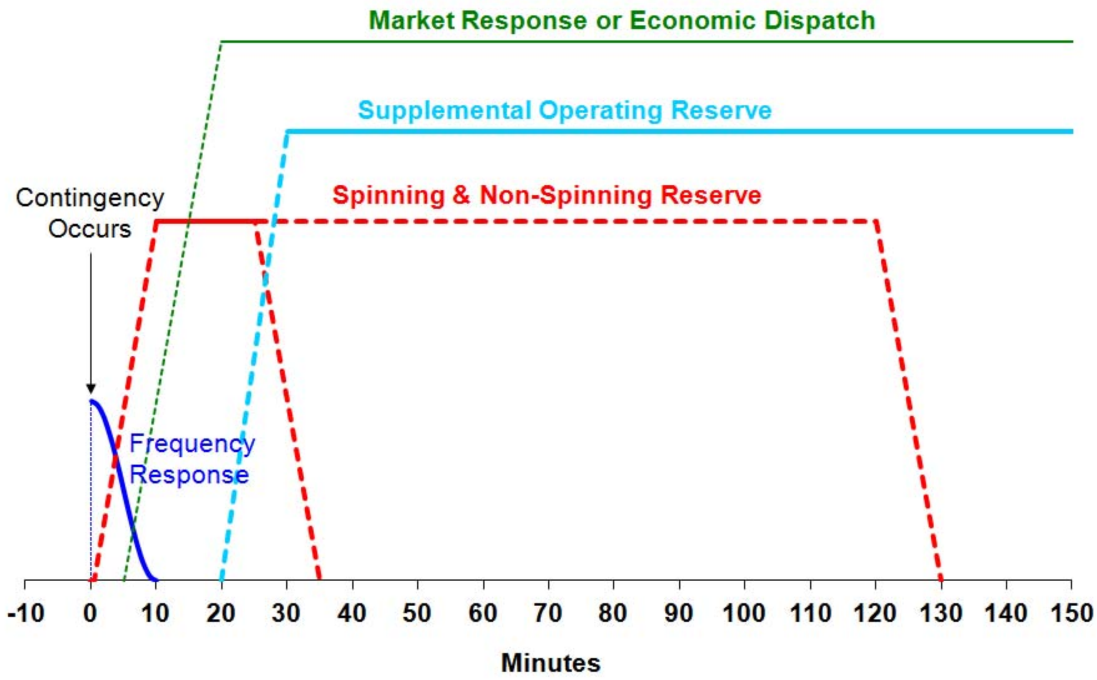

Figure 10 Contingencies are responded to with a series of ancillary services.

Spinning Reserve

Spinning reserve is generation or responsive load capacity that is available to respond to power system contingencies. The resource must begin responding immediately and be fully responsive within ten minutes. Response can be an hour or longer but in practice system operators prefer to release spinning reserves quickly so that the reserves are available to respond to a subsequent event. ISOs run hourly markets for spinning reserve.

Non-spinning Reserve

Non-spinning reserve is very similar to spinning reserve with the same ten minute response requirement. Response need not begin immediately and non-spinning reserve can be supplied by fast-start generation.

Supplemental Operating Reserve

Some ISOs also procure supplemental operating reserve which is similar to non-spinning reserve but fully responsive in 30 minutes.

Regulation

Regulation is the use of on-line generation, responsive load and storage that is equipped with automatic generation control (AGC) and that can change output quickly (MW/min) to track the moment-to-moment fluctuations in customer loads and to correct for the unintended fluctuations in generation as shown by the red curve in Figure 9. Regulation helps to maintain interconnection frequency, manage differences between actual and scheduled power flows between balancing areas, and match generation to load within the balancing area. AGC commands are typically sent about every four seconds.

Regulation performance is beginning to be measured and paid for. PJM currently has the most advanced regulation metrics with scores for correlation, precision, and performance. Faster and more accurate response is paid more.

Following

Following is the slower counterpart to regulation which tracks the sub-hourly trend in customer loads and to correct for the unintended fluctuations in generation as shown by the blue curve in Figure 9. Following is not yet a paid ancillary service but both the CAISO and the MISO are considering establishing markets for following. Historically five-minute energy markets have been able to provide sufficient following response at essentially no cost to the ISO so that an additional ancillary service was not needed. With increased wind and solar penetration there is a concern that the five-minute energy markets will not have sufficient depth to compensate for large wind and solar ramps and a dedicated reserve will be required.

Ancillary Service Prices

ISOs and RTOs operate hourly markets for ancillary services so historic prices are available for analysis. Table 2 provides annual average prices from five ISO/RTOs. While prices vary from region to region and from year to year they can be significant. Prices may have declined recently because of the downturn in the economy and the resulting reduction in electricity demand which eased pressure on capacity. They may also have declined because of the reduction in natural gas prices putting gas on the margin for more hours of the year. ISOs and RTOs have also been aggressive in reducing their need for ancillary services, especially regulation. The expected increase in wind and solar generation may put upward pressure on ancillary service requirements, especially following and non-spin. This may in turn tend to increase ancillary service prices.

Providing Energy and Ancillary Services

A flexible generator can increase profits by optimizing the provision of energy and ancillary services. The optimal selection of which energy and ancillary service products a generating plant should sell changes from hour to hour as the cost of fuel, and the energy and ancillary services market prices vary. With three ancillary services (regulation, spin, and non-spin)[2] there are seven different operating modes. The first three are obvious:

- At times it is most profitable to simply sell energy.
- Regulation and spinning reserve can be sold any time a generating unit is on line and partially loaded.
- Non-spinning reserve can always be sold when the plant is off line.

[2] This example does not include supplemental operating reserve (30 minute reserve) since non-spin is typically a higher price service and the example assumes the market is not exhausted.

Table 2 Some ISOs and RTOs have operated ancillary service markets for 11 years.

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
					Annual Average $/MW-hr						
				California (Reg = up + dn)							
Regulation	**26.9**	**35.5**	**28.7**	**35.2**	**38.5**	**26.1**	**33.4**	**12.6**	**10.6**	**16.1**	**10.0**
Spin	**4.3**	**6.4**	**7.9**	**9.9**	**8.4**	**4.5**	**6.0**	**3.9**	**4.1**	**7.2**	**3.3**
Non-Spin	**1.8**	**3.6**	**4.7**	**3.2**	**2.5**	**2.8**	**1.3**	**1.4**	**0.6**	**1.0**	**0.9**
Replacement	**0.90**	**2.9**	**2.5**	**1.9**	**1.5**	**2.0**	**1.4**				
				ERCOT (Reg = up + dn)							
Regulation		**16.9**	**22.6**	**38.6**	**25.2**	**21.4**	**43.1**	**17.0**	**18.1**	**31.3**	**9.2**
Responsive		**7.3**	**8.3**	**16.6**	**14.6**	**12.6**	**27.2**	**10.0**	**9.1**	**22.9**	**9.1**
Non-Spin		**3.2**	**1.9**	**6.1**	**4.2**	**3.0**	**4.4**	**2.3**	**4.3**	**11.8**	**6.7**
				New York (east)							
Regulation	**18.6**	**28.3**	**22.6**	**39.6**	**55.7**	**56.3**	**59.5**	**37.2**	**28.8**	**11.8**	**10.4**
Spin	**3.0**	**4.3**	**2.4**	**7.6**	**8.4**	**6.8**	**10.1**	**5.1**	**6.2**	**7.4**	**6.0**
Non Spin	**1.5**	**1.0**	**0.3**	**1.5**	**2.3**	**2.7**	**3.1**	**2.5**	**2.3**	**3.9**	**3.8**
30 Minute	**1.2**	**1.0**	**0.3**	**0.4**	**0.6**	**0.9**	**1.1**	**0.5**	**0.1**	**0.1**	**0.3**
				New York (west)							
Regulation	**18.6**	**28.3**	**22.6**	**39.6**	**55.7**	**56.3**	**59.5**	**37.2**	**28.8**	**11.8**	**10.4**
Spin	**2.8**	**4.2**	**2.4**	**4.9**	**6.0**	**5.4**	**6.2**	**4.2**	**4.4**	**3.4**	**3.1**
Non Spin	**1.4**	**1.0**	**0.3**	**0.6**	**0.9**	**1.6**	**1.7**	**1.7**	**0.9**	**0.1**	**1.1**
30 Minute	**1.2**	**1.0**	**0.3**	**0.4**	**0.6**	**0.9**	**1.1**	**0.5**	**0.1**	**0.1**	**0.3**
				MISO							
Regulation								**12.3**	**12.2**	**10.8**	**7.8**
Spin								**4.0**	**4.0**	**2.8**	**2.3**
Non Spin								**0.3**	**1.5**	**1.2**	**1.4**
				New England (Reg + "mileage")							
Regulation			**54.6**	**30.2**	**22.7**	**12.7**	**13.8**	**9.3**	**7.1**	**7.2**	**6.7**
Spin					**0.3**	**0.4**	**1.7**	**0.7**	**1.8**	**1.0**	**1.7**
10 Minute					**0.1**	**0.3**	**1.2**	**0.5**	**1.6**	**0.4**	**1.0**
30 Minute					**0.0**	**0.1**	**0.1**	**0.1**	**0.4**	**0.3**	**1.0**

Four more operating modes are less obvious but contribute significantly to the modeled plant profits:

- The plant can forgo profitable energy sales in order to sell regulation reserve. This is particularly attractive when the price of energy is only somewhat greater than the production cost. The energy profit per MW of capacity is often lower than the almost pure profit offered from the regulation market.
- Similarly, if the price of regulation is less than twice the price of spinning reserve and if energy profit is marginal, it can be more profitable to sell spinning reserve than regulation or energy. This is because the plant has twice as much spinning reserve capability as regulation capability (the plant must be able to move up and down when selling regulation). The minimum operating load is lower when selling spinning reserve (45 MW in the example below) than when selling regulation (79 MW in the example below).

- Conversely, it can be profitable to run the plant at a minimal load even when the energy market does not cover the fuel cost if the regulation market price is high enough.
- As above, it may be more profitable to sell lower priced spinning reserve than higher priced regulation because the minimum plant load required to enable the supply for spinning reserve is lower than the minimum plant load required to sell regulation. The energy market losses are therefore lower when supplying spinning reserve than when supplying regulation.

Lastly, additional profit opportunities would become available if the plant could supply spinning reserve while operating the generators as synchronous condensers and the prime mover shut down.

Modeling a flexible generating plant provides some insights. The example plant has a minimum load of 40% and can fast start and fully load within ten minutes. This allows it to provide 100% of its capacity for non-spinning reserve, 60% of its capacity for spinning reserve, and 30% of its capacity for regulation but not simultaneously. Using 2012 NYISO day-ahead reference bus energy prices and eastern zone ancillary service prices and assuming $3/MMBTU gas results in the operating modes shown in the one week example in Figure 11. When supplying only energy the plant would have an 80% capacity factor and run factor for the full year (lower curve in Figure 11). Annual profits would be $77K/MW.

Allowing the plant to supply ancillary services as well as energy leaves the run factor at 81% but reduces the capacity factor to 64% as the plant frequently backs down to provide reserves. Annual profits increase to over $90K/MW. The shift in energy production, and the supply of regulation, spin, and non-spin are shown in the upper four curves in Figure 11.

Ancillary services are increasingly important for plant profitability as fuel prices rise, as shown in Figure 12. The premise of the figure is a bit misleading since modeled energy and ancillary service prices remain the same as the gas price is adjusted but the concept is still valid. The same principle holds for plants with differing efficiencies. Plant profitability naturally declines as fuel price increases but the profitability with ancillary service sales (blue curve) declines more slowly than the profitability with energy sales alone (red curve).[3]

Figure 13 shows how ancillary service sales are increasingly important as fuel prices increase. In this 2012 NYISO example the hypothetical plant increases profits by 17% with $3/MMBTU gas but by 71% with $4/MMBTU gas. Conversely, a plant with an 80% minimum load will only increase profits by 11% when selling ancillary services and $3/MMBTU gas. Results will differ in different regions and at different locations within the same region, so modeling of the specific plant is required, but the general concept remains sound. Higher fuel prices necessarily result in lower plant utilization and lower profits but ancillary services become an increasing fraction of the total profits the plant is capable of making. Figure 12 also shows that the mix of ancillary services the plant should provide changes as fuel and energy prices change.

[3] This plant might also sell capacity, black start, and reactive power/voltage support.

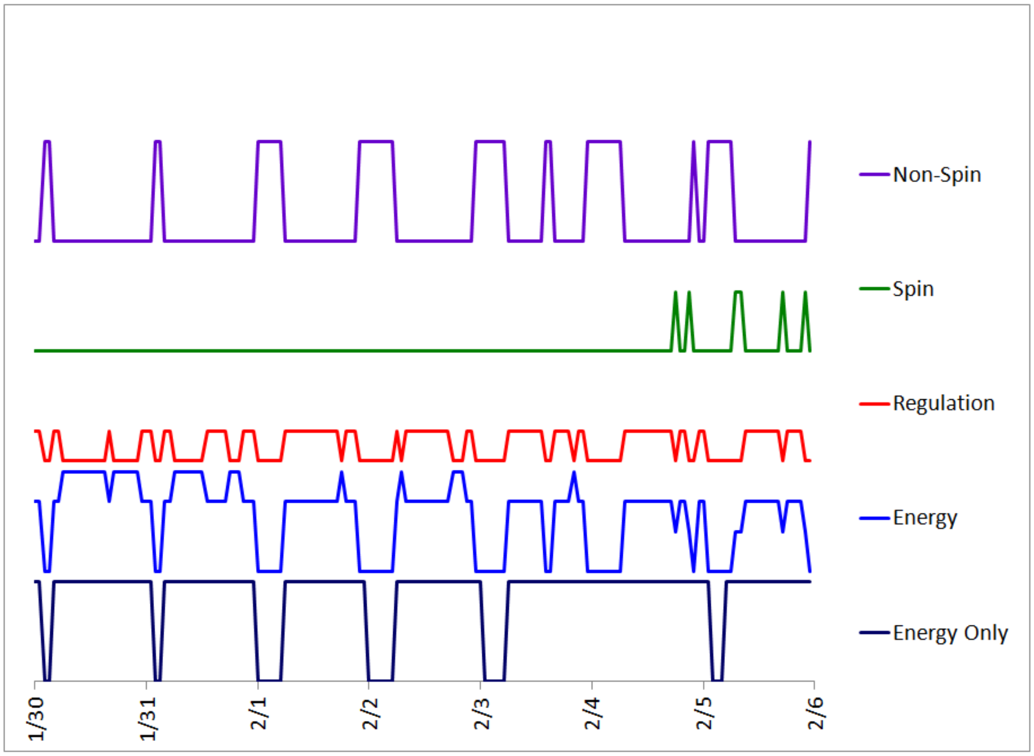

Figure 11 Optimal plant operating mode changes when it is able to supply ancillary services (day-ahead NYISO 2012).

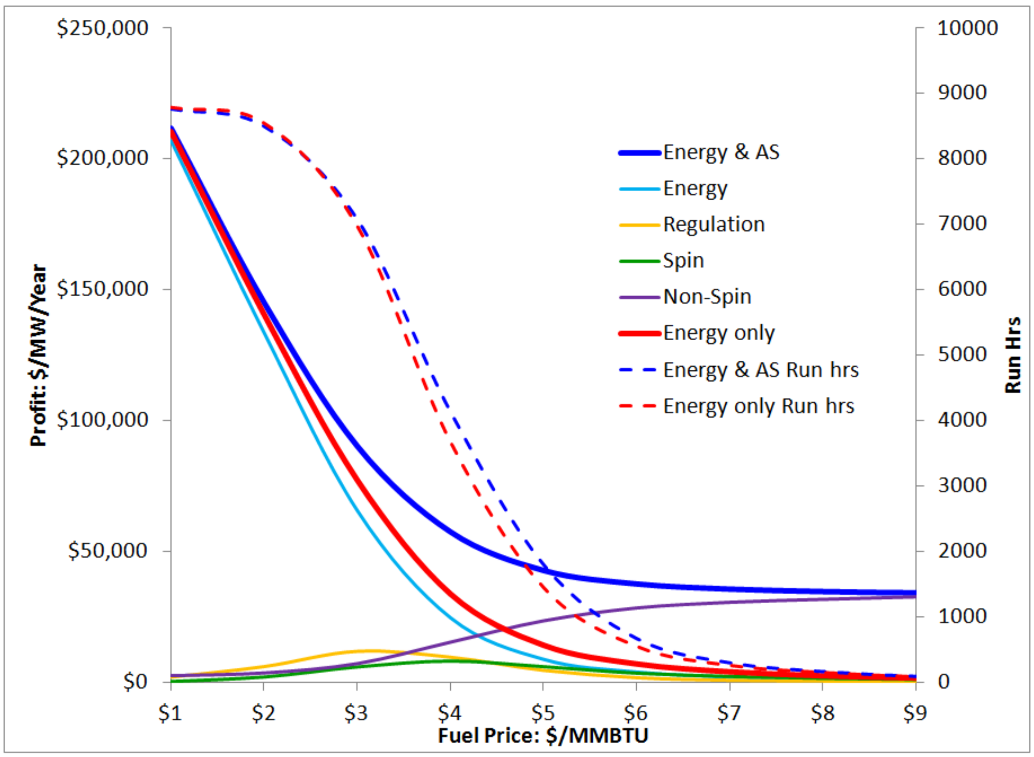

Figure 12 Ancillary services are increasingly important for profits as gas prices rise (NYISO, day-ahead, 2012).

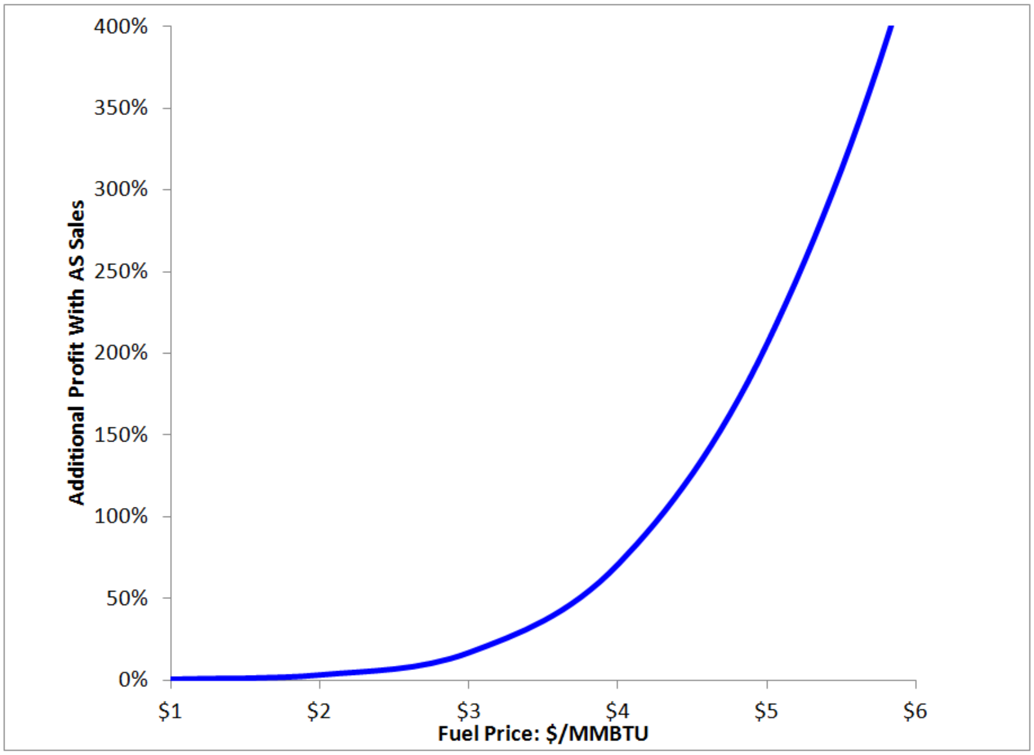

Figure 13 The importance of selling ancillary services increases as fuel prices increase or plant efficiency declines.

Conclusions

The power system requires flexibility to deal with variability and uncertainty. Increased penetration of wind and solar will increase power system variability and uncertainty and the need for flexibility in the rest of the generation fleet. Market regions obtain flexibility through a series of day-ahead, hour-ahead, and five-minute energy markets coupled with ancillary service markets. Ancillary service markets provide dedicated capacity to deal with variability and uncertainty that is faster or larger than the energy markets can compensate for. The same need for flexibility exists in non market areas but the methods system operators use to obtain resources to deal with variability and uncertainty are less transparent.

Generators, responsive loads, and storage compete to provide the flexibility services that system operators require and pay for. This is important because generator costs are not guaranteed to be covered in competitive markets. Generators compete with each other and with responsive loads and storage to sell services the power system values. Generators with greater flexibility are better positioned to profit in energy and ancillary service markets. Because generators are expensive pieces of equipment with long service lives they should be designed and built with as much flexibility as practical so that they are positioned to maximize their profits as power system conditions change over time frames from cycles to years.

Generator flexibility characteristics are not specified directly in terms of energy and ancillary service market quantities. Instead it is the characteristics of the generators that enable them to participate in volatile energy markets and to supply ancillary services. Valuable flexibility characteristics include:

- lower minimum loads
- faster ramp rates
- faster and more accurate AGC response
- greater operating ranges
- higher efficiencies (especially at lower loads)
- faster and lower cost start/stop cycling ability
- governor/frequency response

Together these characteristics allow a generator to offer more ancillary service capability and to move more rapidly between energy and ancillary service markets, responding to rapidly shifting prices and maximizing profits.