Illustrative Examples of Reactive Capability (D-Curves) and Corresponding Compensation under Package E

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September 20, 2022

Summary of Package E Compensation Metric

Flat rate: a generator's revenue is ***MVAR_Capability****Rate*

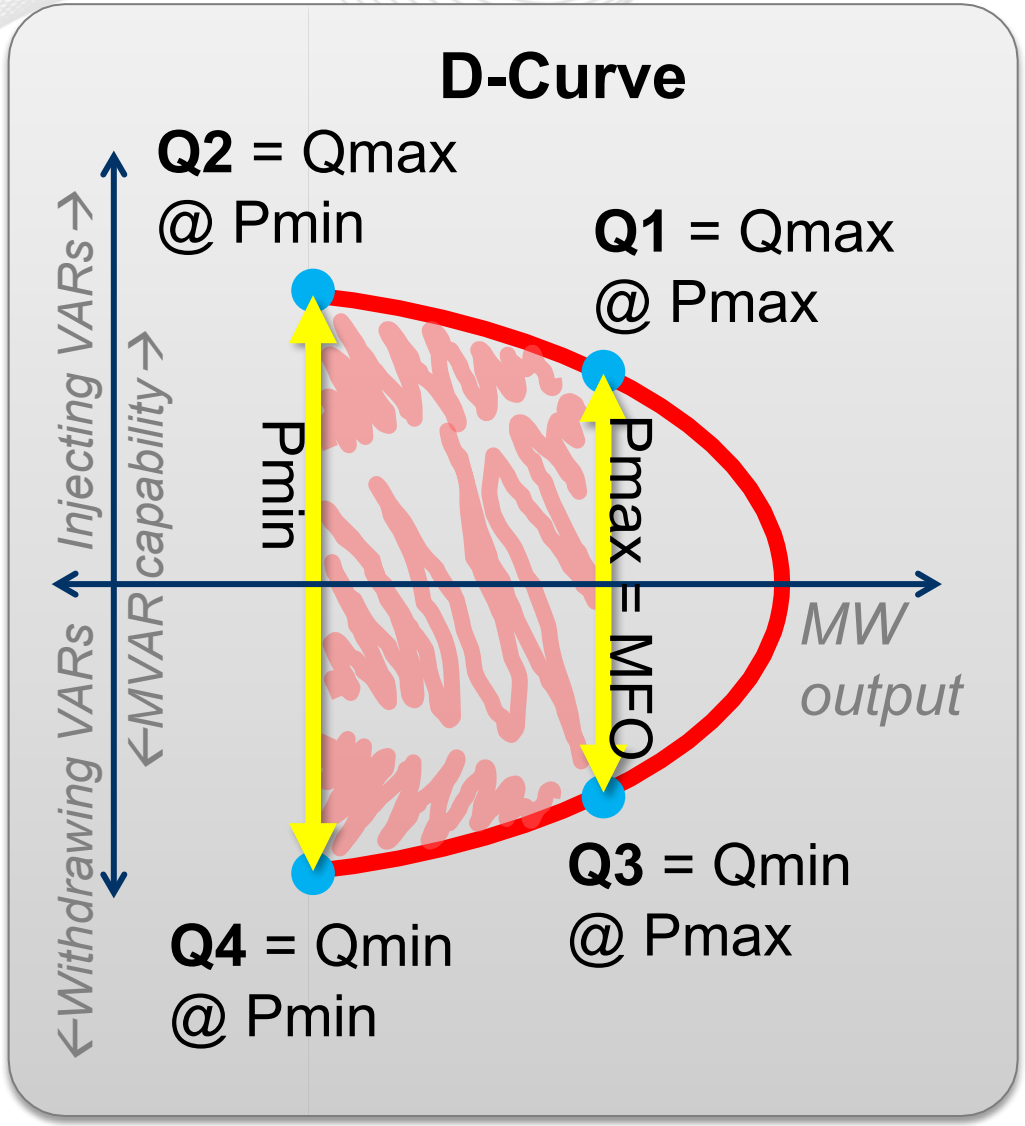
- *For illustration, assume Rate is $1,000/MVAR-yr (hypothetically).*

A generator's **D-curve** shows the maximum reactive capability (both injecting & withdrawing VARs, or "Q") as a function of real power (i.e., MW or "P") output.

- *In general, machine designs mean more MW output means less MVAR capability.*

MVAR_Capability is [average of Q1 and Q2] minus [average of Q3 and Q4]. This basically amounts to: ***injecting capability (averaged at Pmax and Pmin) plus withdrawing capability (averaged at Pmax and Pmin).***

- *VAR withdrawal is negative Q, hence the "minus".*
- *Pmin is the lowest power the generator is capable of making while online (not less than zero).*
- *Pmax is Maximum Facility Output or the functional equivalent.*

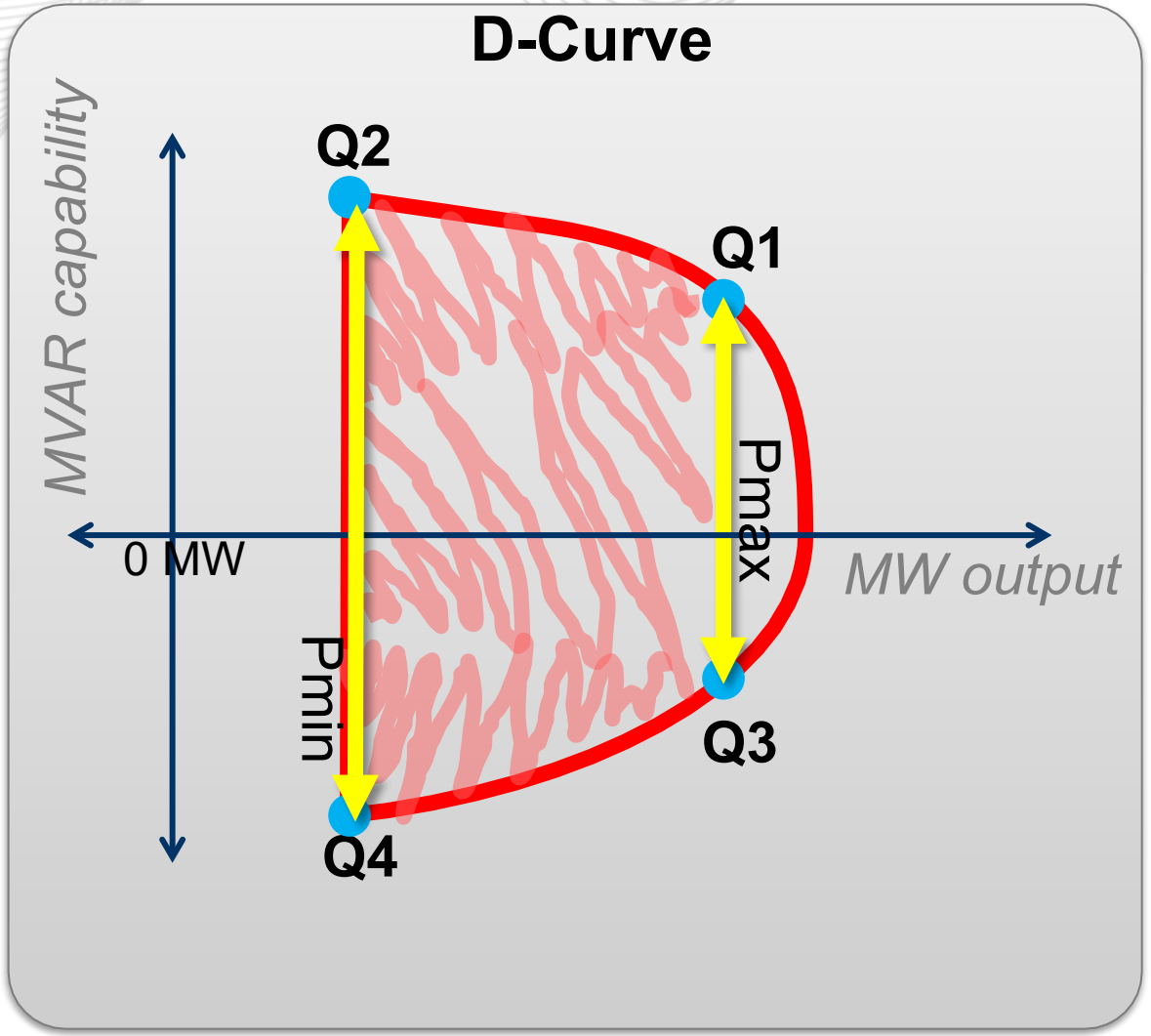


Illustrative Example of a 100 MW Steam Generator

- VAR injection capability:
  - *Q1 at Pmax (100 MW) = **40** MVAR*
  - *Q2 at Pmin (50 MW) = **50** MVAR*
- VAR withdrawal capability:
  - *Q3 at Pmax = **-33** MVAR*
  - *Q4 at Pmin = **-40** MVAR*
- Average(***40,50***) - Average(***-33,-40***) = 81.5
- Compensation = $1,000*81.5 = **$81,500/yr**

Typical interconnection agreements require a minimum reactive capability that amounts to roughly 1/3d of MFO. In theory, the "nose" of the D-curve is typically not available.

Synchronous machine designs generally have lower VAR withdrawal capability than injection capability.

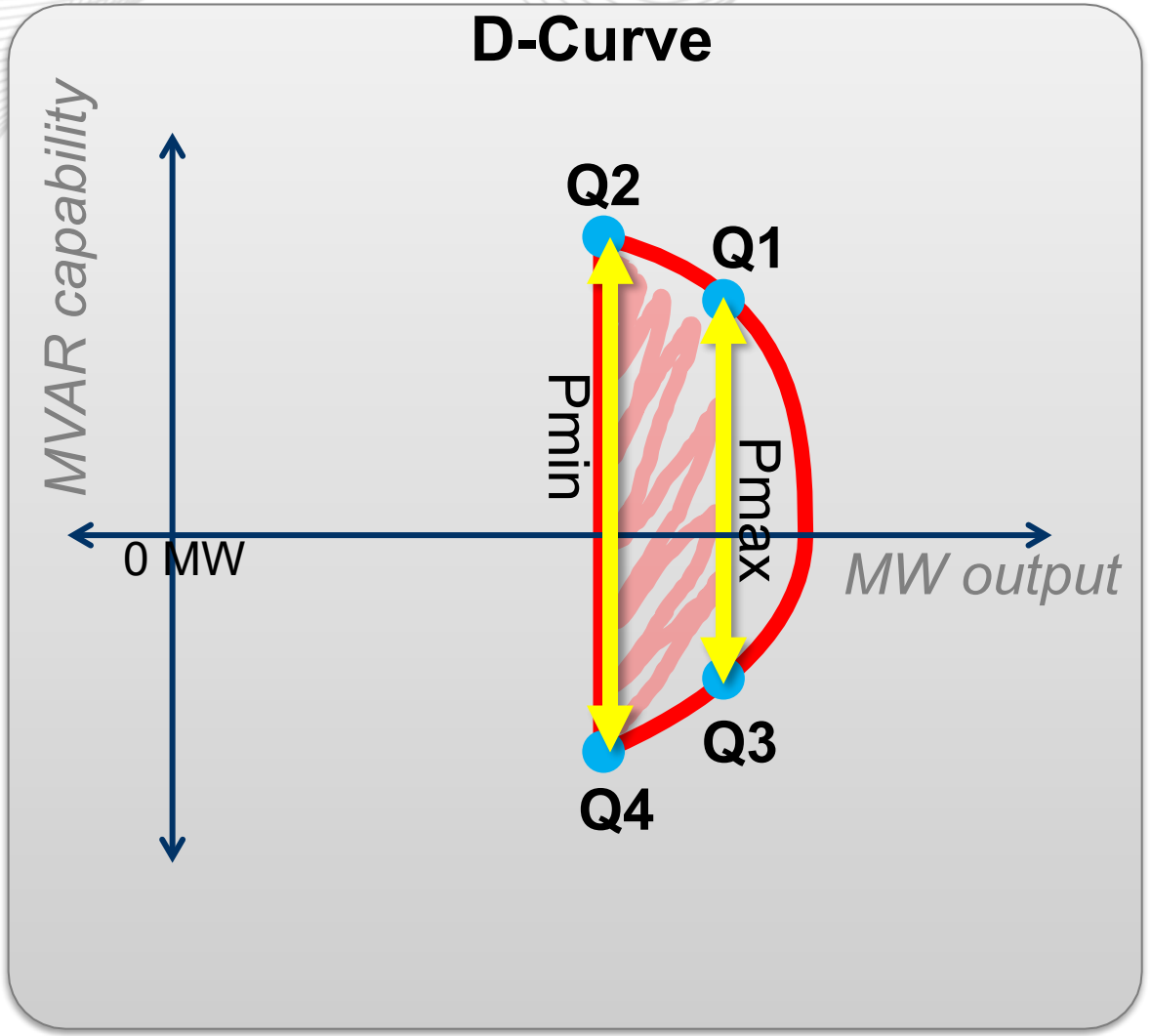


Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a 100 MW Combustion Turbine

- VAR injection capability:
  - *Q1 at Pmax (100 MW) = **40** MVAR*
  - *Q2 at Pmin (80 MW) = **45** MVAR*
- VAR withdrawal capability:
  - *Q3 at Pmax = **-33** MVAR*
  - *Q4 at Pmin = **-35** MVAR*
- Average(***40,45***) – Average(***-33,-35***) = 76.5
- Compensation = $1,000*76.5 = **$76,500/yr**

A CT might have a narrower dispatchable range than a steam generator, which might reduce the reactive capability available to PJM.

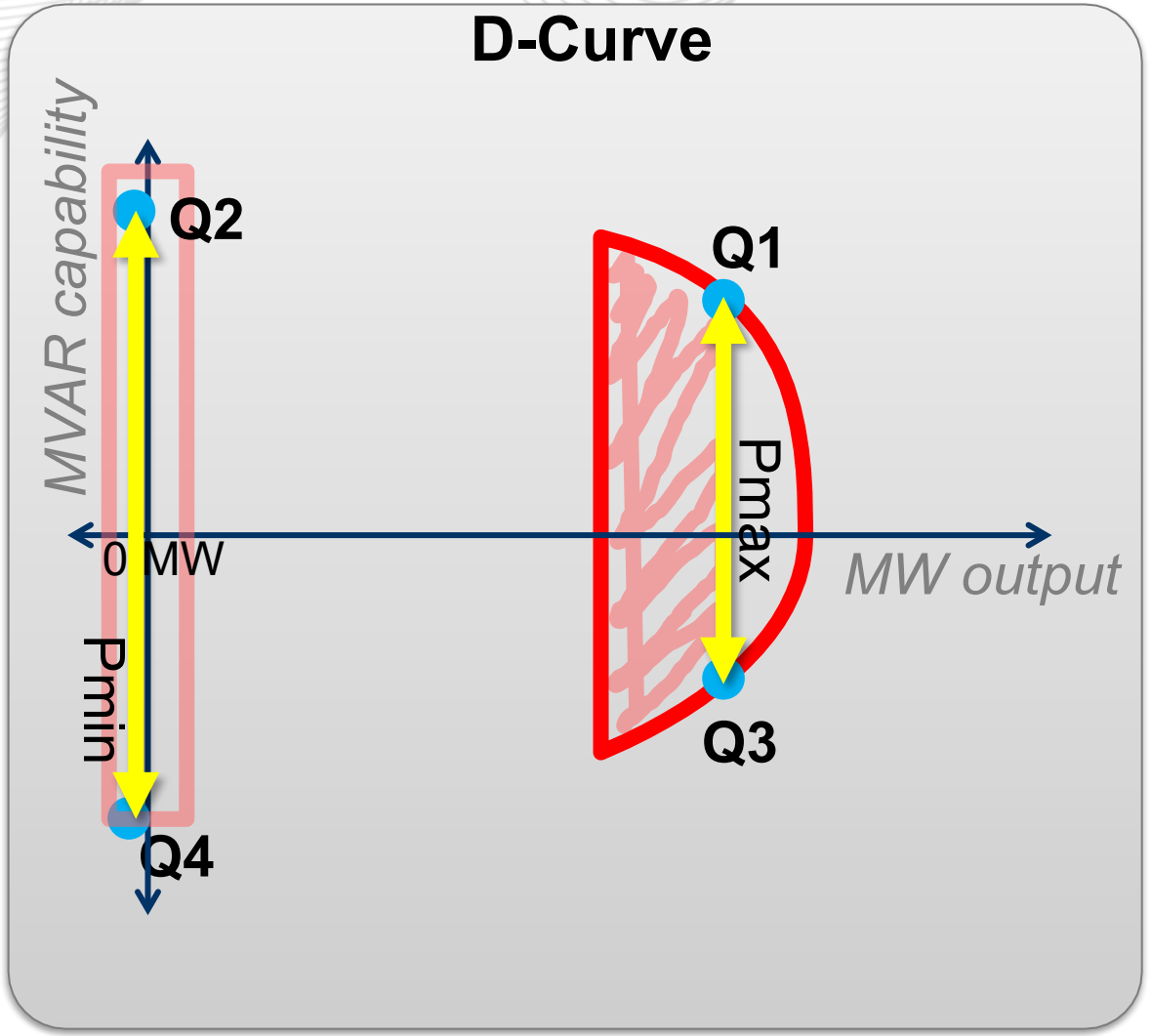


Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a Combustion Turbine
w/ Condensing Mode

A synchronous machine generator with "condensing mode" can operate at 0 MW.

- VAR injection capability:
  - *Q1 = **40** MVAR*
  - *Q2 = **50** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-40** MVAR*
- Average(***40,50)*** – Average(***-33,-40***) = 81.5
- Compensation = $1,000*81.5 = **$81,500/yr**

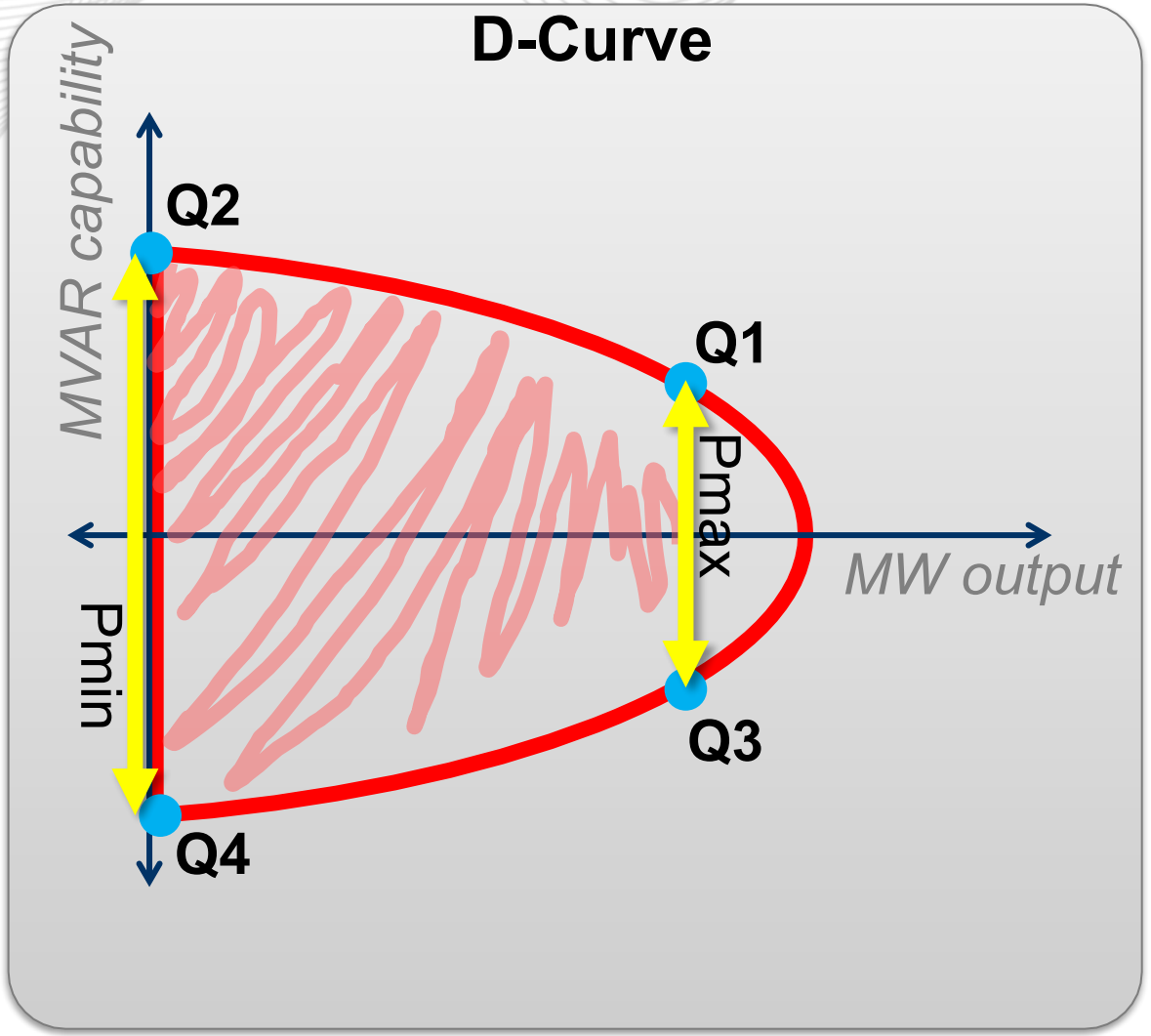


Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a Solar Plant

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **45** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-45** MVAR*
- Average(***33,45***) – Average (***-33,-45***) = 78
- Compensation = $1,000*78 = **$78,000/yr**

Inverter reactive capability matches power capability (they have a circular D-curve at the inverter terminals), however high impedance between PJM and large solar farm inverters reduces the reactive capability.

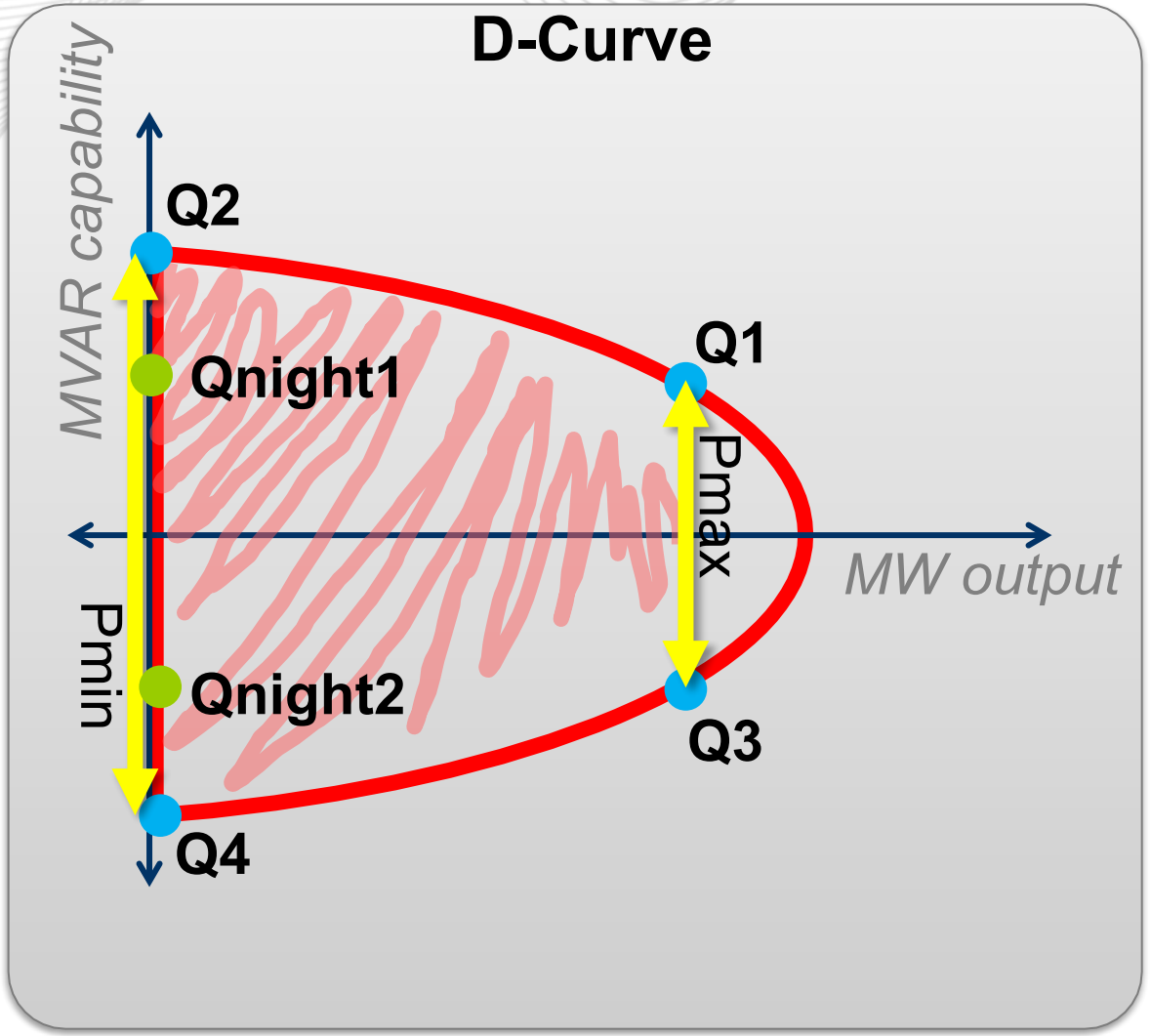


Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a Solar Plant
w/ Reactive at Night Capability

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **45** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-45** MVAR*
- Average(***33,45***) – Average (***-33,-45***) = 78
- Compensation = $1,000*78 = **$78,000/yr**

Reactive capability at 0 MW at night might be lower than capability at 0 MW during the day (i.e., when dispatched to 0 MW). Therefore, no change vs. previous example.

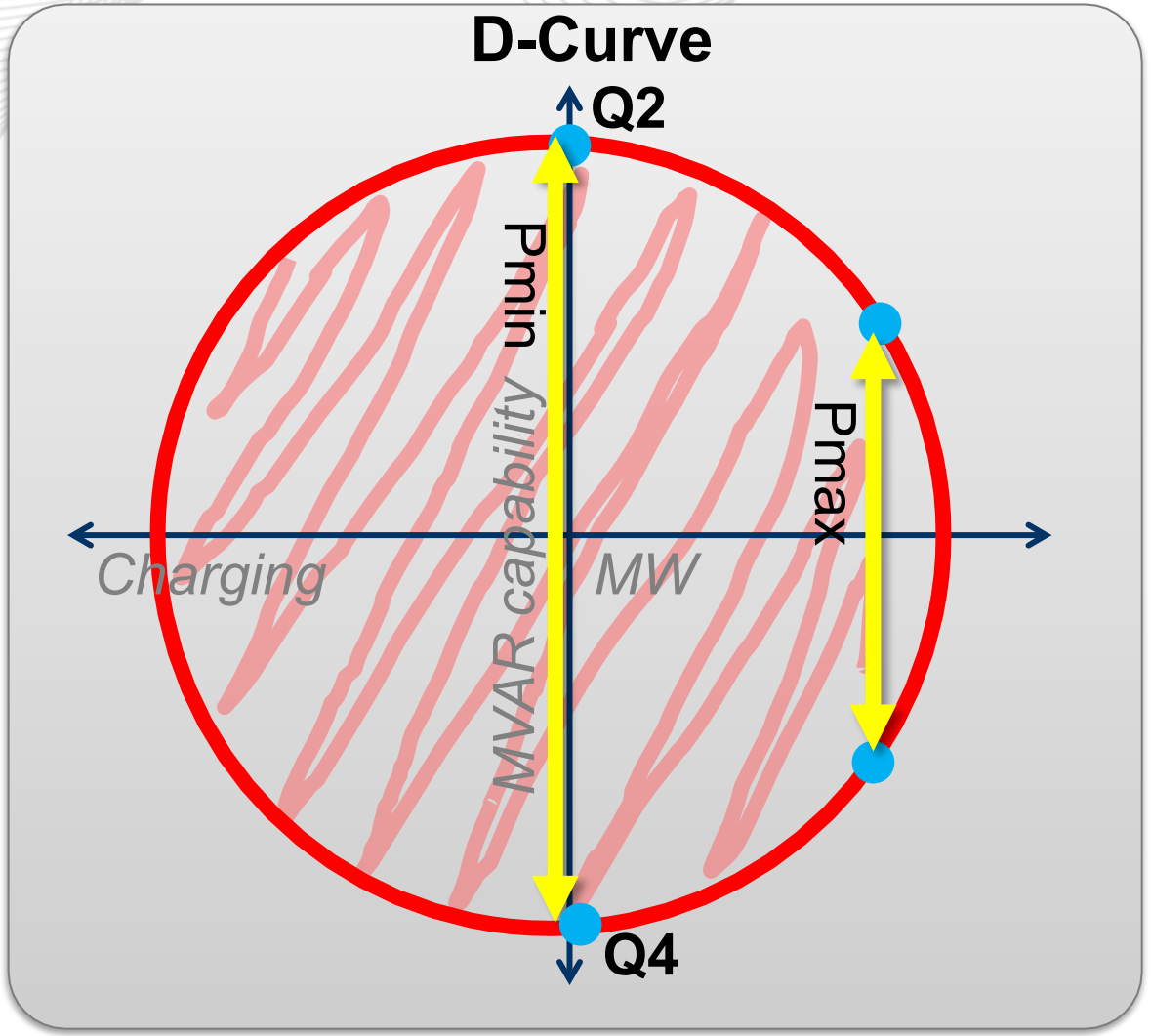


Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a Battery

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **100** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-100** MVAR*
- Average(***33,100***) – Average (***-33,-100***) = 133
- Compensation = $1,000*133 = **$133,000/yr**

Battery inverters would be located close to the POI, with little impedance to PJM. The full circular inverter capability is therefore available to PJM.

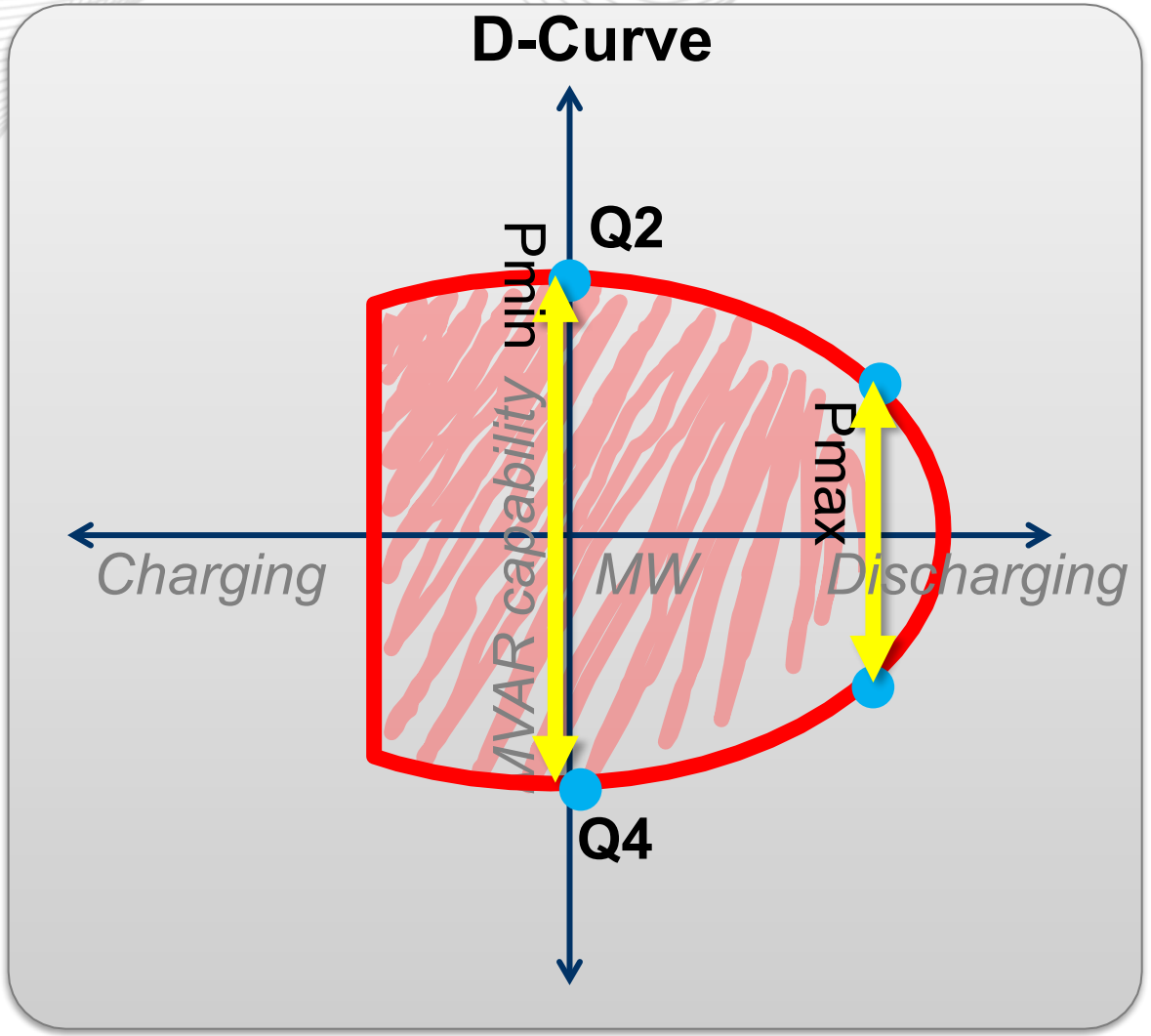


Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a Solar-Battery Hybrid
(Shared Inverters)

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **45** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-45** MVAR*
- Average(***33,45***) – Average (***-33,-45***) = 78
- Compensation = $1,000*78 = **$78,000/yr**

This hypothetical solar-battery hybrid uses the solar inverters to operate the batteries. It is the same as the standalone solar example, except also has charging MW.

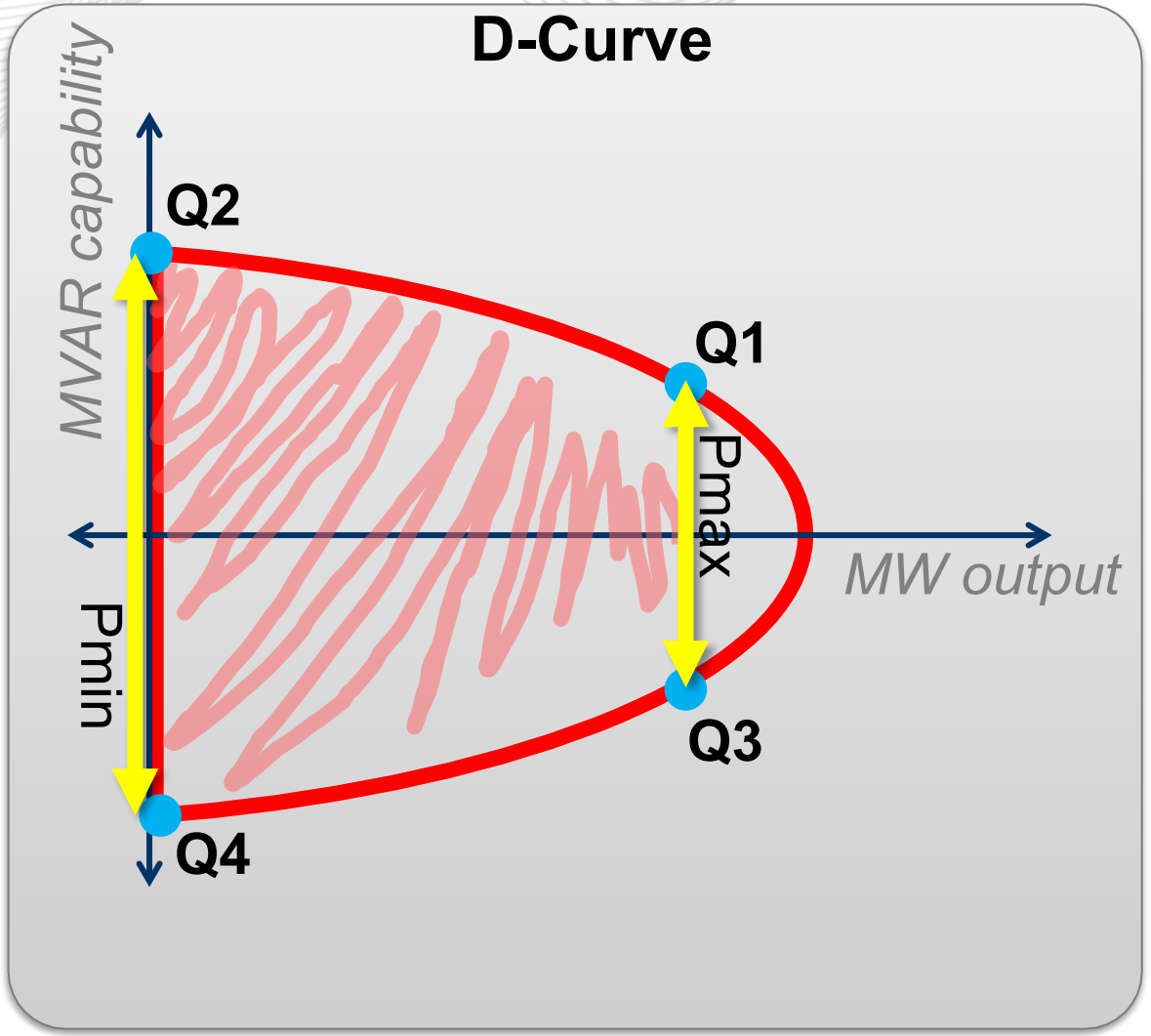


Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of New-Technology Wind Plant

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **45** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-45** MVAR*
- Average(***33,45***) – Average (***-33,-45***) = 78
- Compensation = $1,000*78 = **$78,000/yr**

New wind generator technology is fully inverter-based, similar to solar. This result is the same as the solar example.



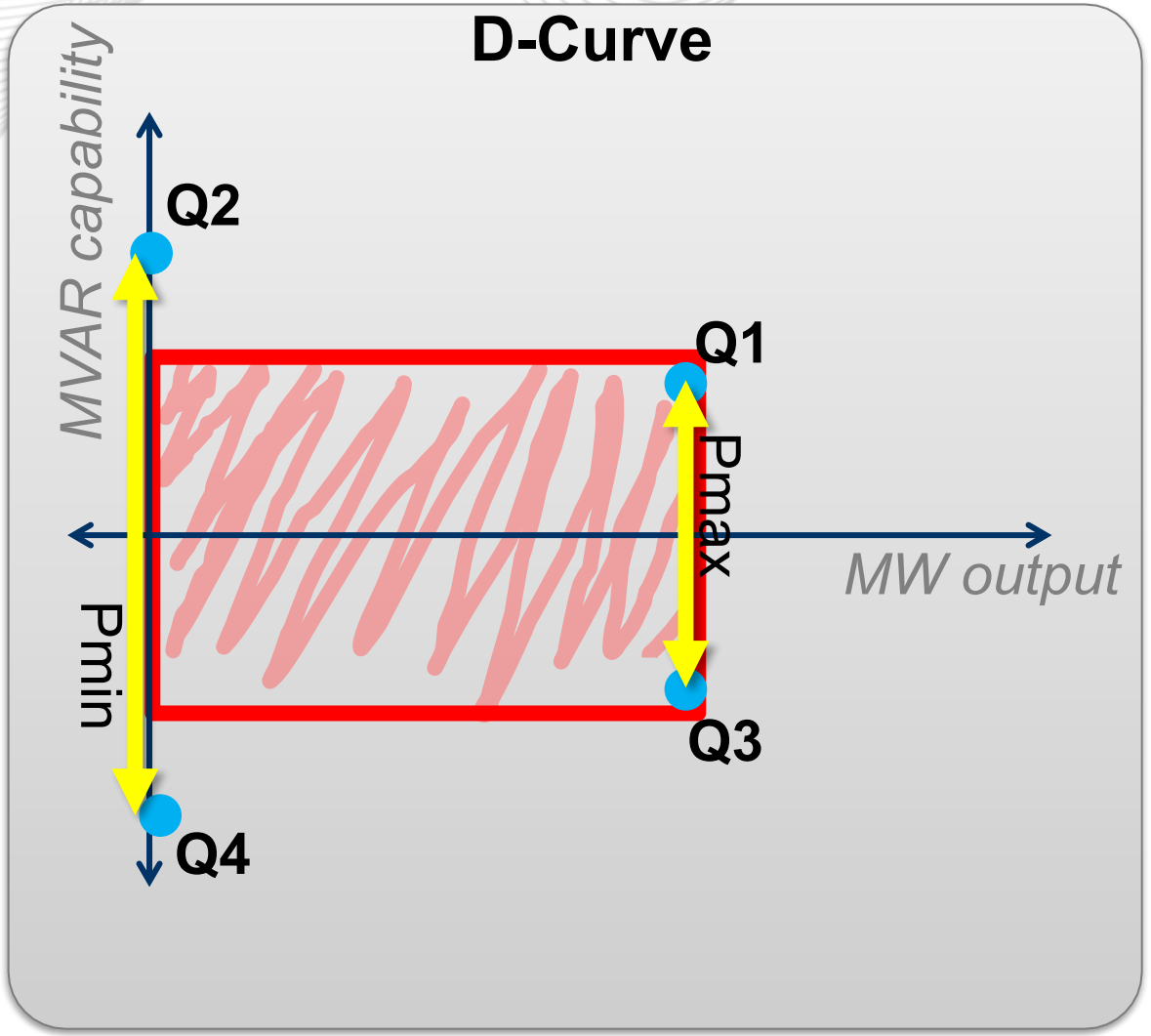
Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of Old-Technology Wind Plant

w/ Full Reactive Capability at All Times

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **33** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-33** MVAR*
- Average(***33,33***) – Average (***-33,-33***) = 66
- Compensation = $1,000*66 = **$66,000/yr**

Old wind generator technology is only partly inverter based. They don't use the generators for reactive, instead using dedicated equipment that doesn't vary with power output..



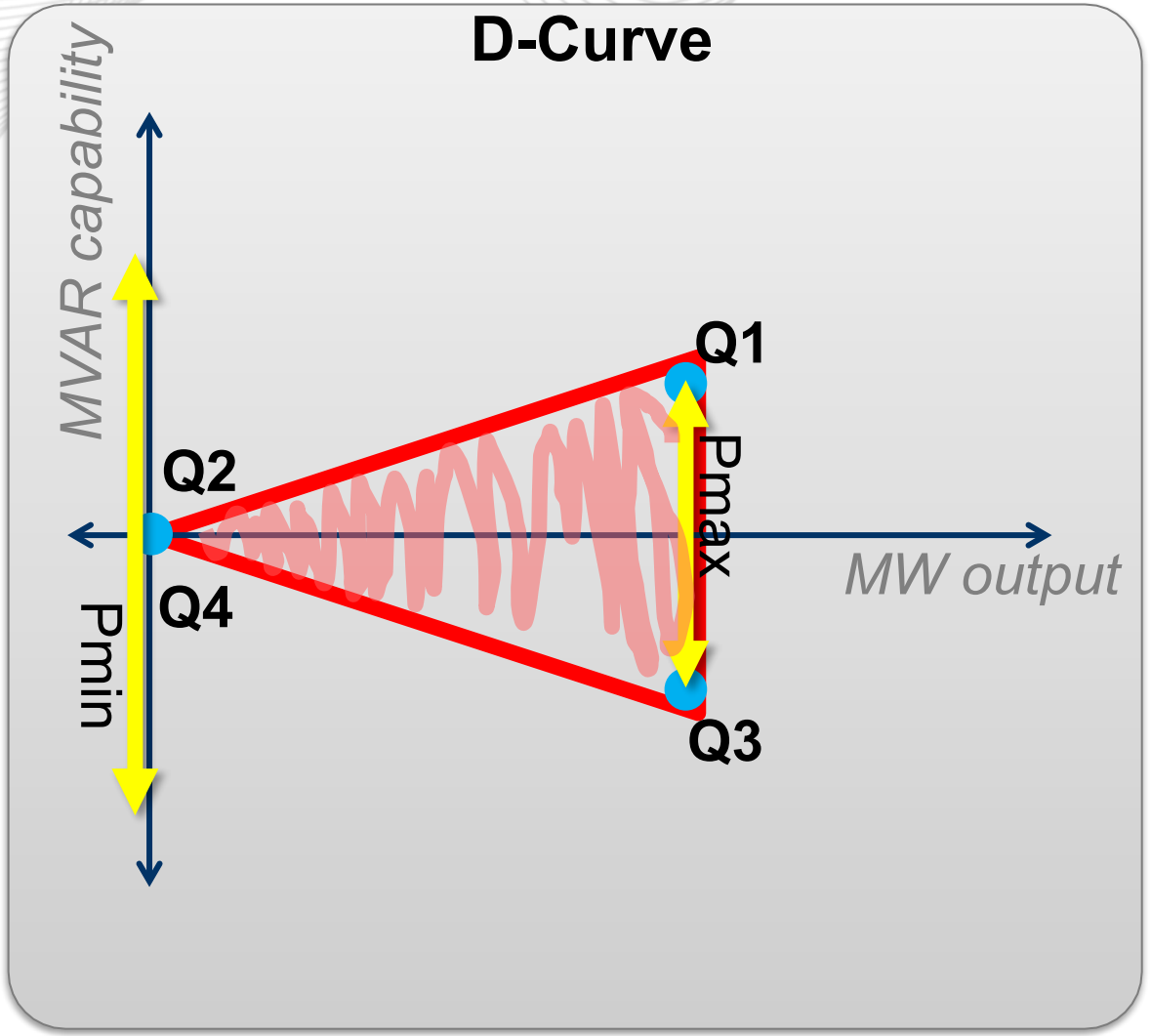
Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of Old-Technology Wind Plant

w/ Fixed Power Factor Control Only as-per ISA

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **0** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-0** MVAR*
- Average(***33,0***) – Average (***-33,-0***) = 33
- Compensation = $1,000*33 = **$33,000/yr**

This example's dedicated VAR equipment was programmed to only provide reactive capability required by the ISA, which is a fixed power factor that drops with lower MW. This is consistent with the ISA power factor obligation, but does not provide the full capability of the equipment.



Hypothetical rate of $1,000/MVAR-yr