Introduction

Installing reciprocating internal combustion engine (RICE) units is a decision requiring an economic and operational assessment of the user’s needs, and while it is true that equipment costs rise with an increased quantity of units, it is important to look beyond those costs to the potential benefits of installing more units. Depending on the application and the user’s specific requirements, the benefits of increased plant reliability and availability can, in certain cases, outweigh the costs of more units. This white paper examines the cost and benefits of increased engine units to reach desired plant output, and makes evaluation recommendations based on plant size and application. The equipment referenced in this paper is based on the electrical capacity (kW) and the representative RICE models reflected in the chart below.

Costs & Benefits

When engine quantity goes up, there is an obvious increase in equipment and installation costs. This paper presents the benefits of adding units to increase plant reliability while measuring the cost impact. For example, high speed reciprocating engine system installed costs range from $1,800-$2,800/kW for a single unit, and medium speed reciprocating engine system installed costs range from $1,000-$1,600/kW for a single unit. Additional square footage cost outpaces plant infrastructure cost. Therefore, construction costs grow at a slower rate than equipment costs. In the chart below of a representative 30 megawatt plant, you can see the total cost, unit quantities, and average selling price per unit. Notice how average selling price goes up with fewer units.

Construction and installation costs are driven by footprint rather than infrastructure. As units increase, a larger footprint is required, which means installation costs go up.
Plants with a combination of varying models and equipment sizes are typically less competitive due to operating costs (maintenance, spare parts, and training). Users will benefit during their initial investment by having larger quantities of a single model rather than a mix of technologies.

**Increased Reliability with Increased Units**

Plant reliability improves in terms of megawatt-hours (MWh) available versus MWh capable with increased units. What is the user’s cost for lost generation and does it differ by application? The user’s criticality requirements for plant output are the most important consideration. The economic cost of additional capacity versus reducing the degree of risk in producing electricity should also be considered. The cost of 100% N-1 reliability brings each option closer together in terms of total installed cost, as seen in the chart below.

**Considering other Factors**

There are several other factors to keep in mind when evaluating the costs and benefits of increased RICE units. It is important to consider the probability of single point failures in the plant, not the unit, by checking singular plant systems. This is a failure mode for plant reliability and availability that cannot be easily determined. It could affect plants of varying sizes the same way, assuming a “single-point” system or plant-wide system is of similar quality and reliability.

The risk of lost generation capacity increases with larger unit quantities due to greater dependency on plant systems. This is offset by the increased availability of electricity resources when a single unit is unavailable.

Site access and/or soil quality can serve as major constraints that limit users to increase the amount of lower output units. For example, with Amazonas in Brazil, site access and soil quality negatively impact the process of moving units, as well as the process of acquiring labor and materials. Lighter, smaller machines are often preferred for areas with significant logistics challenges.

Lead time to reach the commercial operations date can impact this decision, as smaller units are generally lighter and containerized, which can reduce manufacturing, installation, and construction lead times, so the speed to generating revenue or gaining capacity/availability payments is greater.

**How to Evaluate**

Plant criticality may drive the need for increased plant reliability. A user may decide to trade off the costs incurred for critical applications, based on the benefit of N-1 (or greater) reliability to their revenue stream. Users may be willing to pay more for the assurance that in a reliability event, 100% of their load could still be produced.
A unit reliability improvement beyond one additional kilowatt above 100% of the required load has a diminishing return. For example, the additional cost of improving beyond N-1 reliability outweighs the benefit from a purely cost-based perspective. However, some applications, such as hospitals, manufacturers, data centers, and nuclear power plants, often want or need full redundancy, due to the importance of up-time to their business models, and therefore would be willing to purchase up to 2N units to assure their reliability needs are met.

If the success of a user’s business plan is driven by the availability and reliability of their power generation equipment, attention to the unit and plant reliability data should precede a focus on cost. Because of the nature of a critical power application, the additional cost to mitigate the risk of downtime in the system outweighs the increased cost of additional equipment to meet this requirement.

### Plant Revenue Drivers

#### Availability and Capacity Payments

Users receiving capacity payments may be open to larger unit quantities due to lead time and availability. As a result, the payment stream is related to available megawatts. If one unit is down in a one-unit plant, revenue drops by 100%, but if one unit is down in a six unit plant, revenue falls by 17%.

One example of this arrangement is a large-capacity (240 megawatt) plant in South America, where the owner chose to build multiple small generators for an availability contract due to speed in which the units could be operational. Despite the higher investment cost, the owner was able to generate more. However, now that the units are operating for energy rather than idle for capacity, the lower design reliability of these high speed RICE assets is causing increased O&M costs and downtime risks for the user. Fortunately, the plant is still able to produce a significant amount of energy due to having over 400 discrete units at 640 kW each, rather than all of the capacity in fewer units.

### Cost Drivers and Comparisons

#### Capital Expenses

Capital expenses include equipment and construction costs:

- **Equipment**
  - Unit costs ($/kW and total $)
  - Plant “centralized” costs (e.g., air start, water, electrical, etc.)

- **Construction**
  - Installation materials and labor
  - Footprint ($/sq. ft. impact)

Smaller unit quantities end up with the lowest cost for equipment, footprint, and construction, but the relationship isn’t linear. Choice of unit quantity depends on the susceptibility to downtime risk compared to the ability to take on increased capital costs.

The above chart shows N-1 reliability for revenue streams at reduced plant availability. The impact of an hour of down time can become significant. Without including demand charges or premiums, on-peak spot power prices could reach $9,000/MWh in some markets.

#### Generation

Generation faces the same benefits as availability. With the additional availability driving increased revenue, generation capacity can react quickly to increased power demand and electricity production during periods of higher prices. Ancillary services and peaking power are examples of this.

A specific scenario of this is a cooperative user in the U.S. The user had the option of three large units, but opted for five smaller units. This has provided the customer greater flexibility operating at low loads with the ability to respond quickly to dispatch opportunities. The additional cost of logistics (disassembly, time, permit limitations) also played a role in the user’s decision. The additional time to market and cost (almost 100% of the equipment cost) outweighed having power earlier, a smaller building, and less operating flexibility.

#### Plant Capacity

Even though improving plant capacity may not generate revenue, there is an opportunity to serve potential markets with this enhancement.
Reliability Improvement

Reliability helps maintain low operating costs, more stable power generation and risk reduction. How does plant reliability change in meeting demand in an N-1 scenario? This is harder to ascertain because there is increased reliability with increasing sizes limited to technology. High speed engines (≥1200 rpm) have almost 3% less reliability than medium speed engines (<1200 rpm) and twice the forced outage factor.

When comparing values, it is important to focus on the technology’s ability to deliver higher reliability, rather than the quantity of units. That said, assuming the technologies have the same reliability of 95%, the increasing number of units reaches nine “nines” (i.e. 99.999999999%) of reliability at nine units and many more at greater numbers. At lower unit quantities, reliability more closely approaches single system reliability; in this case 99.98%, which is 0.012% less reliability than the plant with nine units.

High speed engine reliability is about 95%, while medium speed is about 98%, and this increase in reliability makes medium speed units reach three “nines” (i.e. 99.999%) of reliability at only three units, and this increases to an almost indiscernible number from 100% at nine units. However, this implies that medium speed plants will offer owner’s greater opportunities for generation and availability revenue due to lower risk.

If a unit goes down, what is the impact to revenues? An hour of downtime increases in an N-1 scenario as unit quantities decrease, and the high reliability of RICE engines and the increasing reliability of multiple units protect the user from an extended downtime event, as costs quickly add up.

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<thead>
<tr>
<th></th>
<th>High Speed RICE</th>
<th>Medium Speed RICE</th>
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</thead>
<tbody>
<tr>
<td>Availability (%)</td>
<td>95.99%</td>
<td>98.22%</td>
</tr>
<tr>
<td>Forced Outage Rate (%)</td>
<td>1.98%</td>
<td>0.85%</td>
</tr>
<tr>
<td>Scheduled Outage Factor (%)</td>
<td>2.47%</td>
<td>1.12%</td>
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<tr>
<td>Mean Time Between Forced Outages (hrs)</td>
<td>1,352</td>
<td>3,583</td>
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<tr>
<td>Mean Down Time (hrs)</td>
<td>51</td>
<td>27</td>
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</tbody>
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Summary and Recommendation

Decreasing unit quantities can carry risk, mostly in terms of the cost of downtime or production below the demanded value. The equipment and construction costs with smaller unit quantities are lower, though smaller unit quantities at bigger sizes and weights impact transportation and logistics costs to a greater degree than smaller, containerized equipment, resulting in convergence of total installed costs. Plants with more units tend to be more resilient to availability and reliability events despite the increased installation cost. These plants provide the user with more revenue generating opportunities, either through availability or generation.

Reliability is a function of equipment type (in the case of engines, high speed vs. medium speed), and attaining “near perfect” reliability in a parallel system occurs at relatively small unit quantities (<10). The criticality to life, property, or the user’s customer base will dictate the level of required redundancy and reliability in order to protect generation capability in the event of an emergency or service disruption. As a result, converging costs may be “thrown out,” depending on the individual user’s circumstances.

In summary, the economics may be outweighed by the size of the risk of a reliability event causing any downtime, regardless of the replacement cost of power or additional capital expense costs at the initial investment. Every user should first evaluate the criticality of their power generation application and how unit reliability affects the business plan. The user should consider how downtime affects their revenue stream, production process, and the additional costs and risks of purchasing power from the grid. Once an acceptable level of risk in reliability and availability is determined, the user should then seek to balance this risk with the total installation cost of the facility and its ability to produce revenue through availability and electricity generation payments.

Sources