# Technology Value Proposition
# Lightbridge

PACE GLOBAL®
A Siemens Business

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# Contents

- Project Objectives and Approach
- Executive Summary
- Generation Development Decision Making
- Required Modifications and Associated Costs
- Summary Impacts on Value Proposition

# Project Objectives and Approach

# Project Background

In August 2012, Lightbridge hired Pace Global to provide a third-party opinion of Lightbridge's nuclear fuel technology value proposition and target U.S. markets for the technology. Pace Global evaluated costs to purchase power and build new generation capacity, developed high-level estimates of owner costs, identified additional technology considerations, and identified the addressable market for Lightbridge's technology. While Pace Global specifically considered the market for existing U.S. four-loop pressurized water reactor (PWR) nuclear power plants, there are many PWR reactors worldwide that could benefit from Lightbridge's fuel solution.

# Project Scope and Approach

## Value Proposition Key Questions

- On what basis will U.S. nuclear plant operators decide to purchase Lightbridge's fuel technology? How will this be different for plants in utility-centric vs. market-centric regions of the U.S.?
- What key primary and secondary systems will require substantial retrofitting to accommodate Lightbridge's fuel technology; and what will they cost the operators?
- What nuclear safety and monitoring program changes will be required?
- What will the U.S. Nuclear Regulatory Commission (NRC) approval process cost the operators?

## Pace Global's Approach

1. **Review Value Proposition** – review the overall business proposition from a nuclear operator's perspective, considering the potential benefits and risks of Lightbridge's fuel technology.
2. **Review Power Uprate Plant Modifications and Costs** – evaluate the key primary systems likely to need modification to accept Lightbridge's fuel and provided high-level cost estimates to adapt these systems.
3. **Determine Wholesale Power Prices for Validating Lightbridge's Value Proposition -** develop indicative forward wholesale power price forecasts and levelized cost of energy analysis to understand how nuclear operators in utility- and market-centric regions will assess the benefits of Lightbridge's technology.
4. **Conduct Risk-Adjusted Economic and Financial Analysis** – develop a levelized cost model to evaluate the cost tradeoffs from an operator's perspective.

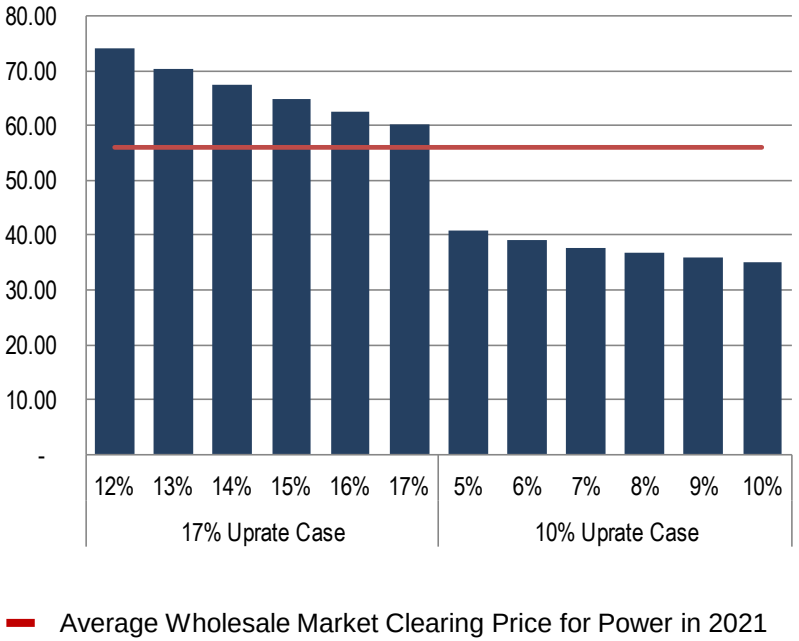
# Executive Summary

# Power Uprate Economics for the Lightbridge Fuel Remain Attractive

## Westinghouse 4-Loop Reactor Uprate Opportunity

- The economics of Lighbridge's nominal 10% capacity uprate are attractive since the uprate's estimated levelized cost of generation should be below the expected market price for power in 2021 and that of most incremental power uprates on fossil-fueled units. Note that 2021 is when Lightbridge expects the first reloaded batch core installation will take place.
- However, the levelized cost of Lightbridge's nominal 17% capacity uprate is significantly above the expected market price for power in 2021. Thus the nominal 17% uprate may only be attractive in utility-centric regions.
- Furthermore, the generation that an owner can expect is reduced by the design and operating limits of existing equipment and the fact that most units have already been to uprated to some extent.
- Further, uprate costs are expected to be
  - $85 million for units to add 7-8% capacity, which will not require a steam generator replacement.
  - $384 million for units to add 13-14% capacity, which will require a steam generator replacement.

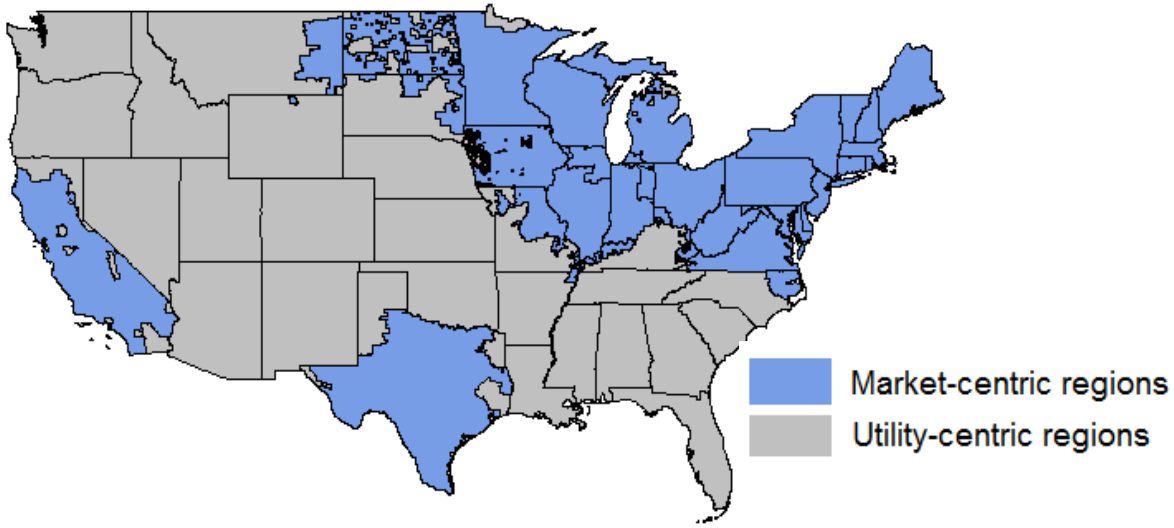
**Levelized Cost of Generation Comparison with Average 2012 Wholesale Market Clearing Price,**
2012$/ MWh



# Generation Development Decision Making

# Whether the Nuclear Plant Operator Is Located in a Utility- or Market-Centric Environment Will Impact Decision Making

## Utility-Centric vs. Market-Centric Areas




**Market-centric regions** – wholesale power prices will determine the operator benefit of switching to Lightbridge's technology.

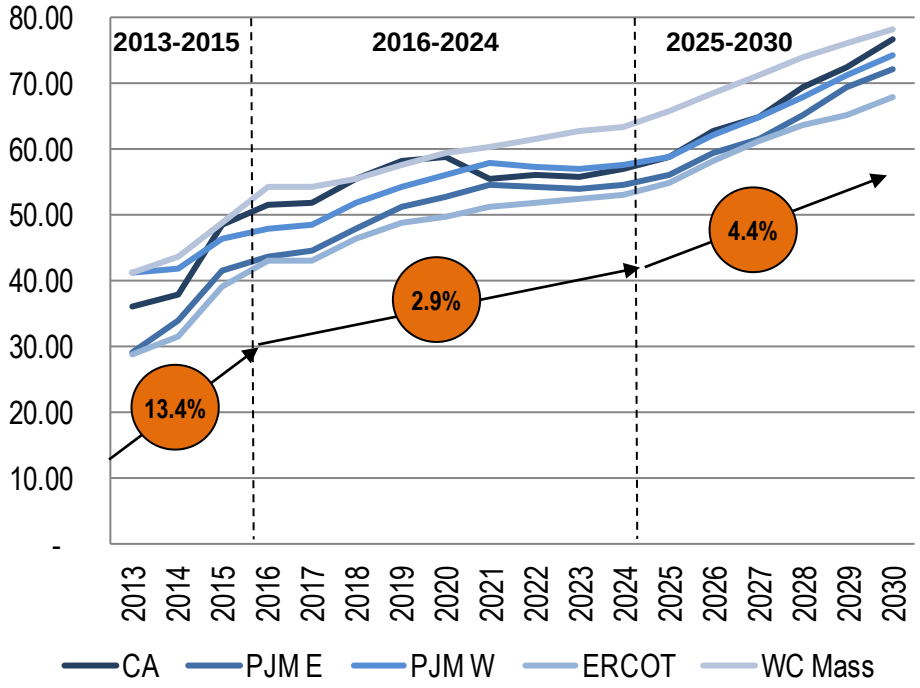
**Utility-centric regions** – operators with load obligations will seek the lowest incremental cost of supply.

| | Market-Centric | Utility-Centric |
|---|---|---|
| Plant Dispatch | • Central dispatch of all plants by independent system operator (ISO) | • Dominant utility balances regional system and dispatches units |
| Wholesale Markets | • Competitive access for independent power producers (IPPs), with all generators required to dispatch into central market | • Incumbent utility controls market and can contract bilaterally with IPPs |
| Retail Markets | • Retail choice exists for customers in certain states | • Integrated utilities control generation, transmission, and distribution to customers |

# Wholesale Power Prices Are Expected to Average $56.00/ MWh in 2021

## Market-Centric Wholesale Power Prices

**Indicative All-Hours Wholesale Power Prices,** 2012$/MWh




- 2013 wholesale power prices are expected to vary from $29-41/ MWh.
- Overall, all-hours wholesale power prices are expected to increase at 4.5% p.a.
- Across key competitive markets, wholesale power prices are expected to increase 13.4% p.a. from 2013-2015, 2.9% p.a. from 2016-2023, and 4.4% p.a. from 2024-2030.
- However, in 2021, when Lightbridge expects the first operational core installation, power prices across all markets are expected to average $56.00/ MWh, with the highest-priced market being New England ($60.40/ MWh) and lowest being ERCOT ($51.40/MWh) .

Note: Power prices in any given year may vary substantially from the above estimates based on such factors as fuel prices, pending coal plant retirements, cost of new unit entry, the pace of renewable generation adoption, the impact of pending regulations (emissions or renewable related), material and equipment price increases, and increased labor rates.

# In Utility-Centric Markets, Deciding What Generation to Add Is More Closely Linked with the Cost of Generation

## Utility-Centric Generation Development

- Generation planners in utility-centric markets look for the lowest generation cost alternative to meet their loads.
- Planners will compare to the lowest cost of generation alternative, perhaps a new combined-cycle plant for large load requirements or incremental power upgrades at existing facilities.
    - Larger generation requirements (several hundred MWs) are likely to come from new resources. Combined-cycle technologies offer the lowest levelized cost of generation of all technologies ($65-70/MWh).
    - Smaller amounts (up to a few hundred MWs) may come from smaller new units or uprates of existing coal, gas or nuclear-fueled technology. One regulated utility recently indicated a levelized cost of $111/ MWh to convert a 237 MW coal boiler to use natural gas.
- Reserve margins, which are currently high, will decline more rapidly in coal-dominated markets as units are retired.

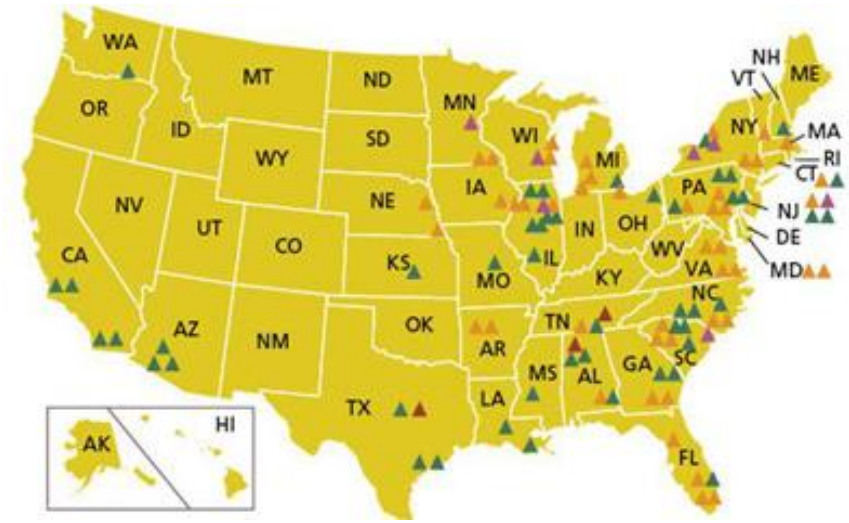
**Reserve Margins and Trends**

| Region | Current Reserve Margins, % | Reserve Margin Trends | Observations |
|---|---|---|---|
| TVA (SERC-N) | 33% | Down | Over 2 GW of retirements are on the books or seem likely. |
| Southern (SERC-SE) | 42% | Neutral | While reserve margin seems to be stable in the near future, there is some risk associated with current and future coal regulations post 2015. |
| Entergy (SERC-W) | 59% | Neutral | 70% of generation is from gas so increased coal regulations will have little impact. |
| VACAR (SERC-E) | 22% | Neutral | Reserve margins are tighter and Duke is retiring coal, but replacing it one-for-one with gas and building new nuclear generation. |
| NWPP | 27% | Neutral | Reserve margins should remain high, but much of generation is wind and hydro which have associated uncertainty. Only 1,190MW of nuclear generation installed. |
| MISO | 25% | Down | Coal retirements should be coming; replacement is not as assured as in VACAR. |

# While There Is More Upgradable Capacity in Market-Centric Areas, Ownership Is Diffuse, Challenging Business Development Efforts

## Operating Westinghouse 4-Loop Nuclear Power Plants in the U.S.

### U.S. Commercial Nuclear Power Reactors




Source: U.S. Nuclear Regulatory Commission

- Most Westinghouse 4-loop reactors are located in market-centric areas offering a little over 33GW of U.S. market potential.
- However, most of the potential in the utility-centric regions can be accessed via Duke, Southern, and TVA.
- Only Exelon operates more than two Westinghouse 4-loop units in the market-centric region.

### Westinghouse 4-Loop Units

| | Market-Centric | Utility-Centric |
|---|---|---|
| No. Plants | 11 | 6 |
| No. Units | 19 | 10 |
| Capacity, MW | 22,276 | 11,257 |

### Westinghouse 4-Loop Plants by Region

| Market-Centric | Utility-Centric |
|---|---|
| Braidwood | Catawba |
| Byron | McGuire |
| Callaway | Sequoyah |
| Comanche Peak | Vogtle |
| D.C. Cook | Watts Bar |
| Diablo Canyon | Wolf Creek |
| Indian Point | |
| Millstone | |
| Salem | |
| Seabrook | |
| South Texas | |

Source: *http://www.nrc.gov/info-finder/reactor/#listAlpha*

# Required Modifications and Associated Costs

# While Conversion Costs Are Substantial, the Benefits Are Also Significant

## Summary Assessment of Required Plant Changes and Costs

**The average realizable uprate potential without steam generator replacement is ~7-8%.**

- Tube plugging in older steam generators reduces potential .
- The only four-loop units not already uprated use ice condenser safety systems, which have no additional design margin due to the ice bed designs and will be prohibitively expensive to uprate. The average current uprate percentage for the remaining reactors is 3.17%.

**The average realizable uprate potential with steam generator replacement is ~13-14%.**

- As reactor vendors moved to new product lines, design margins were reduced. Therefore, the newer designs often have a smaller opportunity for increased power without modification.

**Power uprate costs could approach $85 million for a 7-8% uprate and $384 million for a 13-14% uprate.**

- Plant programs affected include: system/component margin analyses, design basis calculation review, including LOCA airborne-release dose and fuel-handling accident dose, equipment qualification, high-energy line break criteria, flow-accelerated corrosion, and emergency plan, among others.
- Licensing of the plant associated with the new fuel and power levels will require significant effort and analyses – likely >> $10M (engineering, license amendment development, NRC application review, request for additional information (RAI) response) and is included in the above cost estimates. These costs are appropriate for the first uprate and will decline significantly for subsequent relicensings.

| Power Uprate | Remaining Realizable Uprate Potential | Pace Global Cost Estimate |
|---|---|---|
| Without Steam Generator | 7-8% | $85.0 million |
| With Steam Generator | 13-14% | $384.0 million |
| New EPR Design | Unknown | Unknown |

# Additional Plant and Program Considerations

| Technical Area | Effect on Power Uprate |
|---|---|
| Emergency Core Cooling Systems (ECCS) | The margin available in the systems used to mitigate the consequences of an accident (ECCS) will need to be reassessed to accommodate the new fuel design at the higher licensed power levels. |
| Auxiliary Heat Removal Systems (Chiller/HVAC Systems) | At higher power levels, the heat generated throughout the reactor containment and other plant areas will increase. Experience at other plants indicates that existing chiller HVAC systems are marginal at the licensed power level. Replacement of HVAC chillers is likely. |
| Equipment Cooling Water Systems | Systems used to remove the heat generated by equipment and the reactor auxiliaries generally use heat exchangers in closed systems to allow the heat to be transferred to the cooling tower, river, ocean or other ultimate heat sink used by the plant. These heat exchangers will likely need to be replaced if the power level is increased in the 12% –17% range. |
| Licensing Process | The cost of licensing the plant at a higher power level requires a number of associated analyses, submittals, discussions, and sometimes hearings to obtain regulatory approval. The owner will need a staff dedicated to this process and will pay for consultant studies. In addition, the owner will pay the cost of NRC staff reviewing the application. |
| Program Updates and Revisions | Each plant has a number of programs related to maintenance, testing, and operation of the plant, each of which has been developed over time and approved by the NRC staff. With a substantial power uprate, many of these programs will require revision to incorporate the new equipment and plant conditions. The annual cost of performing the work associated with these programs may also increase. |

# The Average Current Uprate Percentage for Reactors Without Ice Condensers Is 3.17%

## Uprate Status of Westinghouse 4-Loop Plants

- Of the 18 Westinghouse 4-Loop reactors, all but two have had some uprate. Because these units have ice condensers, it is unlikely they will ever be uprated.
- While some units may still have an 8-9% available margin without a steam generator replacement, many may only have a 5-6% margin, which will limit what owners will spend.
- With uprate potential capped at 17% and about 3% already in use, 14% potential remains, thus limiting economic benefit for some owners.

Note: Braidwood and Byron are currently undergoing an uprate that will increase their uprate percentages to 6.75%, thus reducing their future uprate potentials.

| Plant | Current Uprate Percent |
|---|---|
| Braidwood | 5.00% |
| Byron | 5.00% |
| Millstone 3 | 5.00% |
| Indian Point 3 | 4.85% |
| Callaway | 4.50% |
| Wolf Creek | 4.50% |
| Indian Point 2 | 3.20% |
| Diablo Canyon | 2.00% |
| Seabrook | 1.70% |
| Vogtle | 1.70% |
| D.C. Cook* | 1.66% |
| Salem | 1.40% |
| South Texas | 1.40% |
| Watts Bar* | 1.40% |
| Sequoyah* | 1.30% |
| Comanche Peak | 1.00% |
| Catawba* | 0.00% |
| Mc Guire* | 0.00% |

*Ice Condenser Plant

# The Technology Review Identified Several Additional Considerations

## Additional Technology Considerations

- The increased decay heat characteristics and behavior of Lightbridge's spent fuel under normal conditions are yet to be adequately proven to regulators.
- The size and metal of the steam generators may change for the larger uprate case where a replacement steam generator will be required; some change in in the steam generator (SG) design is required for the additional heat transfer margin. This could result in an increase in the SG size, required metal, and coolant inventories.
- With increased volume flows in safety systems, pipe whip restraints and jet impingement analyses may require review.
- Increasing pump flow through existing systems will increase the pressure drop in the system; many of the safety systems have specific pressure requirements to support safe operation.
- The increase in reactor power may require a reanalysis of the containment system.
- Many of the reactor containments designed for the Westinghouse 4-Loop plants have minimal available space for added components or size increases. Adding containment to accommodate additional components will not be economical.
- Limits on uprate potential are plant specific and will include
    - Steam generator capacity, limited by size and weight
    - Steam flow and feedwater flow constraints due to piping material and sizes
    - Containment analysis for operational heat loads and accident effects

# Summary Impacts on Value Proposition

# Core Value Proposition Assumptions

| Key Value Proposition Assumptions | |
|---|---|
| **Category** | **Assumptions** |
| Technology | • Technology most applicable to Westinghouse 4-Loop reactors.<br>• Average nuclear power plant capacity factor of 88%.<br>• Cost of reactor refueling outage is $22.5 million per outage. |
| Timing | • As of June 2012, the NRC projects 16 power uprates will occur between 2012 and 2016, potentially reducing the potential fuel upgrade market.<br>• Approximately 40-45% of the core will be replaced in each refueling, so plant owners will not receive the full benefit of the new fuel in the first year of operation.<br>• Economics favor an earlier uprate with a longer depreciation period.<br>• The length of a reactor outage is 30 days.<br>• A reactor outage occurs every 18 months with conventional fuel and every 24 months with Lightbridge's technology for uprate levels up to 10%.<br>• LTA operational testing starts in 2018, and the first partial core reload starts will begin in 2021-2022. |
| Commercial | • The fuel compensation model includes a substantial up-front payment. Utilities prefer a payment model that matches cash flow to fuel usage. Similarly, fuel fabricators prefer to match payments that they make to their revenue streams. Lightbridge may have to accept a payment model that better matches the financial models followed by its customers.<br>• Lightbridge enters into technology licensing agreements with fuel fabricators whereby Lightbridge is paid an upfront technology access fee plus a royalty fee per assembly produced. |

# Upgrade Potential for Certain Units Is Limited in Some Cases

## Westinghouse 4-Loop Reactor Market Potential

| Plant | Operator | Power Market | License Expiration | Remaining License, Yrs | No. Units | Name Plate Capacity, MW | Current Uprate, % | Uprate Potential (10%), MW | Uprate Potential (17%), MW |
|---|---|---|---|---|---|---|---|---|---|
| Braidwood | Excelon | Market Centric | 2026 & 2027 | 14 | 2 | 2,330 | 5.00% | 116.5 | 279.6 |
| Byron | Excelon | Market Centric | 2024 & 2026 | 12 | 2 | 2,300 | 5.00% | 115.0 | 276.0 |
| Callaway | Union El. | Market Centric | 2024 | 12 | 1 | 1,236 | 4.50% | 68.0 | 154.5 |
| Comanche Peak | Luminant | Market Centric | 2033 & 2034 | 21 | 2 | 2,350 | 1.00% | 211.5 | 376.0 |
| D.C. Cook | Ind. Mich. Power | Market Centric | 2034 & 2037 | 22 | 2 | 2,069 | 1.66% | 172.6 | 317.4 |
| Diablo Canyon | PG&E | Market Centric | 2024 & 2025 | 12 | 2 | 2,300 | 2.00% | 184.0 | 345.0 |
| Indian Point | Entergy | Market Centric | 2013 & 2015 | 1 | 2 | 2,045 | 4.85% | 105.3 | 248.5 |
| Millstone | Dominion | Market Centric | 2045 | 33 | 1 | 1,227 | 5.00% | 61.4 | 147.2 |
| Salem | PSEG | Market Centric | 2036 & 2040 | 24 | 2 | 2,304 | 1.40% | 198.1 | 359.4 |
| Seabrook | Nextera | Market Centric | 2030 | 18 | 1 | 1,295 | 1.70% | 107.5 | 198.1 |
| South Texas | STP | Market Centric | 2027 & 2028 | 15 | 2 | 2,820 | 1.40% | 242.5 | 439.9 |
| Catawba | Duke | Utility Centric | 2043 | 31 | 2 | 2,258 | 0% | | |
| McGuire | Duke | Utility Centric | 2041 & 2043 | 29 | 2 | 2,200 | 0% | | |
| Sequoyah | TVA | Utility Centric | 2020 & 2021 | 8 | 2 | 2,274 | 1.30% | | |
| Vogtle | Southern Co. | Utility Centric | 2047 & 2049 | 35 | 2 | 2,236 | 1.70% | 185.6 | 342.1 |
| Watts Bar | TVA | Utility Centric | 2035 | 23 | 1 | 1,123 | 1.40% | | |
| Wolf Creek | Wolf Creek Nuc. | Utility Centric | 2045 | 33 | 1 | 1,166 | 4.50% | 64.1 | 145.8 |
| Total | | | | | | | | 1,832.1 | 3,629.5 |
| | | Market Centric | | 16.7 | 19 | 22,276 | 3.05% | 1,582.4 | 3,141.7 |
| | | Utility Centric | | 26.5 | 10 | 11,257 | 1.48% | 249.7 | 487.9 |

Ice Condenser Units

# As of June, 16 Power Uprates Were in Planning, which Could Further Reduce the Potential Market for Lightbridge's Solution

**Planned Nuclear Plant Uprates**

| Fiscal Year | Total Power Uprates Expected | Measurement Uncertainty Recapture Power Uprates | Stretch Power Uprates | Extended Power Uprates | Megawatts Thermal | Approximate Megawatts Electric |
|---|---|---|---|---|---|---|
| 2012 | 3 | 1 | 0 | 2 | 932 | 311 |
| 2013 | 7 | 5 | 0 | 2 | 1,142 | 380 |
| 2014 | 2 | 0 | 0 | 2 | 254 | 85 |
| 2015 | 3 | 1 | 0 | 2 | 930 | 310 |
| 2016 | 1 | 0 | 0 | 1 | 435 | 145 |
| **TOTAL** | **16** | **7** | **0** | **9** | **3,693** | **1,231** |

Note: expected uprate applications are current as of June 2012.

# Project Economics Are Generally Attractive for Nuclear Plant Owners

## Conversion Cost Comparison

*All cost in USD millions*

| Operational Impact Estimates | | |
|---|---|---|
| Base Unit Capacity, MWe | 1,100 | 1,100 |
| Uprate Case | 8.0% | 14.0% |
| Additional Unit Capacity, MWe | 88 | 154 |
| New Unit Capacity, MWe | 1,188 | 1,254 |
| Incrimental Annual Net Generation from Capacity, MWh | 678,374 | 1,187,155 |
| Incrimental Annual Net Generation from Avoided Refueling Outage, MWh | 142,560 | - |
| Total Incrimental Annual Net Generation, MWh | 820,934 | 1,187,155 |

| Incrimental Levelized Cost of Energy Estimates, USD/ MWh | | |
|---|---|---|
| Capital Expense w/out Heat Sinks | 12.16 | 37.99 |
| Variable O&M | 2.06 | 2.06 |
| Fixed O&M Reduction | (1.07) | (1.50) |
| Avoided Refuleing Outage Cost Savings | (4.57) | - |
| Conventional Fuel Cost | 8.38 | 8.38 |
| LB fuel cost adder and technology licensing fees | 19.40 | 20.23 |
| Decommissioning | 0.22 | 0.22 |
| LCOE w/out Heat Sinks, USD/ MWh | 36.68 | 67.46 |

| Conversion Cost Estimates | | |
|---|---|---|
| Uprate Case | 8.0% | 14.0% |
| Upgraded Component | | |
| Main Condenser | - | 70.0 |
| Turbine | 15.0 | 60.0 |
| Generator | - | 20.0 |
| Steam Generators * | - | 50.0 |
| Condensate & Feed Pumps | - | 10.0 |
| Reactor Coolant Systems | - | 28.0 |
| Piping | - | 50.0 |
| Main Transformer | - | 15.0 |
| Auxiliary Transformer | - | 3.0 |
| Reserve Transformer | - | 3.0 |
| Chemical Treatment & Volume | - | 3.0 |
| Control Rods | - | 2.0 |
| ECCS Systems | 15.0 | 15.0 |
| Chiller Systems | 25.0 | 25.0 |
| Equipment Cooling Water | 10.0 | 10.0 |
| Regulatory Licensing | 15.0 | 15.0 |
| Program Updates and Revisions | 5.0 | 5.0 |
| Total w/ out Heat Sinks | 85.0 | 384.0 |
| Upgrade Cost, $/kW | 965.9 | 2,493.5 |

| Greenfield Nuclear Assumptions | |
|---|---|
| Capacity Factor, % | 88% |
| Variable O&M, $/MWh | 2.06 |
| Fixed O&M, $/kW-yr | 93.86 |
| Fuel Cost, USD/ MWh | 8.38 |
| WACC | 10% |
| Assumed remaining Reactor Life, yrs | 20 |
| Capital Recovery Factor, % | 11.7% |
| Waste, $/MWh | 0.73 |
| Decommissioning, $/MWh | 0.22 |
| Assumed Wholesale Power Price, $/MWh | 56.03 |

| Impacts for 10% Uprate Only | |
|---|---|
| Refueling Cycle change from 18 to 24 months => 1 fewer Refueling Outage Over 6 year period | |
| Avoided Refuleing Outage Cost, 000 | 22,500 |
| Refueling Outage Time, Days | 30.0 |