# High Temperature Superconductivity Market Readiness Review

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

Office of Electricity Delivery and Energy Reliability

*Investigation of the status of HTS technology, the requirements of key applications and barriers to future success*

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## Content of Report

This report was prepared by Navigant Consulting Inc.[1] This report was prepared for the US Department of Energy, Office of Electricity Delivery and Energy Reliability. The report summarizes our findings from an evaluation of various technical, cost and market-related factors pertaining to high temperature superconductor materials, wire and devices. The work presented in this report represents our best efforts and judgments based on the best information available at the time that we prepared this report. Navigant Consulting, Inc. is not responsible for the reader's use of, or reliance upon, the report, nor any decisions based on the report. NAVIGANT CONSULTING, INC. DOES NOT MAKE ANY REPRESENTATIONS, OR WARRANTIES, EXPRESSED OR IMPLIED.  Readers of the report are advised that they assume all liabilities incurred by them, or third parties, as a result of their reliance on the report, or the data, information, findings and opinions contained in the report.

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- Sumitomo Electric
- Rockwell
- General Electric
- Rolls Royce
- Praxair
- Air Products and Chemicals
- BOC

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# The Department of Energy's Office of Electricity Delivery and Energy Reliability (OE) requested a detailed investigation of HTS technology, markets and the barriers to commercial success.

- OE's mission is to lead a national effort to help modernize and expand America's electric delivery system to ensure economic and national security.

- OE's Superconductivity Program has been successful in developing high temperature superconductivity (HTS) technology to a point where it is being applied in important energy demonstrations.

- NCI proposed to support OE by investigating the current status of HTS technology development, the markets for key HTS technologies in order to assist OE in understanding the barriers to long term commercial success.

# NCI has analyzed the key issues facing HTS to assess the technology and its ability to support commercial markets.

## The Technology

**Can HTS technology be developed to provide a compelling set of benefits for important market applications?**

- Are the market requirements for technology performance and price well understood?
- Can HTS technology meet any of these targets today?
- Can HTS technology be improved to meet some or all of these targets in the future?
- Do we understand the resource requirements for improving HTS technology to meet the market requirements?
- Does the HTS community believe that the desired results can be achieved?
- Do we understand how long it will take to improve HTS technology to meet the market requirements?

## The Market

**Can attractive markets be developed by leveraging the benefits of HTS technologies?**

- Are there market segments that could benefit from a technology offering higher capacity, higher efficiency, smaller size, or lighter weight?
- Could the benefits of HTS create new applications built on the value it provides?
- Do we understand how long it will take to develop market applications for HTS to a significant size?
- Does HTS technology offer a compelling value proposition for capturing a significant share of these markets in a reasonable timeframe?

# Government support is critical for advancing HTS technology and bringing it to market.

- Significant R&D and technology development work remains to be done.
- The strongest near term markets for HTS are not in utility and energy applications.
  - Military and science applications value the technology attributes most.
  - Other applications, such as transportation are likely to be important.
  - Niche applications will likely be key early markets in energy, but more experimentation is required.
- The Government's HTS program needs to focus on developing the technology to achieve the critical wire performance targets as the top priority.
  - It also needs to fully support development of ancillary technologies such as cryogenics, cryostats and dielectrics and the business models required to properly deploy these technologies in the utility environment.
- The Government's program plan needs to provide long term support for HTS technology through the development and commercialization phases.
- To reduce risk and maximize benefit, the DOE HTS program should include a combination of research, application studies and phased demonstrations.

## In addition to wire cost and performance improvement, significant work will be required on devices for utility and energy applications.

- 2G HTS wire cost and performance goals required for early commercial energy and utility applications will not be achieved until after 2010.
- Once HTS wire is on track to achieve the goals, there will be much more work required to design, develop, and test devices that will leverage the benefits of the technology.
  - Experience from the current round of cable demonstration projects will help map out the needs and objectives for additional rounds of cable demonstrations that will target understanding benefits.
  - In other areas, such as fault current limiters and transformers, we need to build devices, test them in the lab and in the field before we understand the real value propositions.
  - In each device area, we will need to perform several rounds of testing and verification before the utility industry will consider these devices in lieu of their traditional solutions.

## How large are the markets for these devices and how long will it take to develop them?

- The most attractive attributes of HTS technology appear to be related to the small and light characteristics of devices when used in important energy applications.
- The application benefits of HTS devices will not be fully understood until several demonstrations can be performed in each segment.
  - Experimentation is required in order to understand the impact of key benefits, such as low impedance, fault current limiting, high power density and low losses.
  - Utility planners do not have the knowledge and the tools to adequately account for many of these benefits.
- Business models need to be developed that provide utilities with operations and maintenance support required for cryogenic systems.
- Market development will require continued government support to offset added cost and risk for early demonstration projects before a real commercial market will develop.

**We need to do a better job of engaging the utility customers in order to accelerate the adoption of HTS technology.**

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# Commercial success for HTS technology in the important energy and utility applications will take longer than previously predicted.

- 2G HTS wire technology does not currently meet any of the application requirements today that will support a commercial market.
- Lab research has proven that 2G HTS wire can achieve the required performance targets, as we currently understand them.
  - The key issues are around whether or not the technology can be transitioned to high volume, low cost manufacturing processes.
- The technology performance requirements for the various applications must be clarified further to ensure successful commercialization and market entry.
- The HTS community believes very strongly that the desired cost and performance targets can be achieved.
- We have a reasonable idea of the time that will be required to achieve the market requirements, but based on past experience it is likely to take longer than most of the current estimates.

***Long term government support at or above the current levels will be necessary to commercialize HTS technology.***

# Each of the technology platforms – wire, cryogenics and dielectrics – must provide sufficient performance at a price that each HTS application can support.

## HTS Technology Platforms

### HTS Wire

- 1G wire is being deployed in initial system prototypes, but does not support the performance and price requirements for commercial applications
- A consensus has developed around the need to move to 2G wire to meet price and performance requirements
  - 2G materials' cost is lower
  - Improved in-field performance at higher temperatures
  - Better mechanical properties
- In the near-term, cost of HTS wire is a barrier to commercialization.

### Cryogenics

- Cryogenics costs are a significant share of total HTS system cost, and will limit the market as a result
- Systems for larger cable projects can be designed today to be highly reliable, but effective business models for service must be developed
- More efficient and cost effective cryocoolers are critical to the value proposition for HTS applications
- Advanced technology cryocoolers need to be scaled up to larger sizes and the efficiency and reliability needs to be proven
- Application-specific, optimized cryostats are also critical, and their development is needed for cable and other applications.

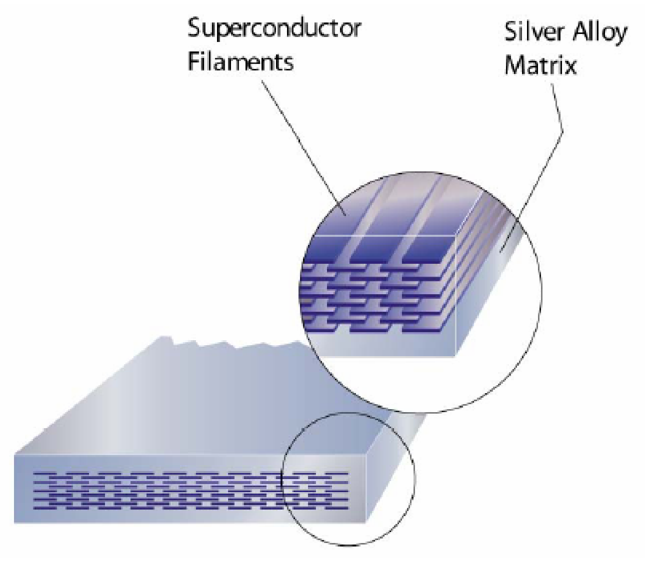
### Dielectrics

- Experience with dielectrics has been mixed, and in some cases has been the source of major technical problems.
- Most experience has been adopted from traditional dielectric approaches in oil filled devices, with very little focus on cold system dielectrics.
- Voids in insulation may become particularly vulnerable at cryogenic temperatures.
- While some research has been done in this area, the ultimate success of HTS technology depends heavily on dielectric systems designed to operate in cryogenic environments

# Early HTS development produced BSCCO-based 1G wire, whose manufacturers include American Superconductor and Sumitomo Electric.

- BSCCO wire technology (1G) was successfully developed as part of the DOE HTS program
- Several manufacturers produce 1G wire, almost all of which has gone into demonstration projects that include:
  - Cable demonstrations
  - SuperVAR
  - Navy propulsion motor
- In the US, 1G wire is currently produced for commercial sale by American Superconductor
- Sumitomo Electric continues to develop 1G technology, and has demonstrated performance of 500 A/cm

1G BSCCO Wire



Source: American Superconductor

**Production 1G HTS wire can deliver about 350 A/cm of performance, at a cost of $125/kA-m today; the lower limit on cost is about $80/kA-m.**

# The HTS industry currently consumes approximately 1000 km of 1G wire per year.

- The major applications have been underground cable demonstration projects, and rotating equipment prototypes.
- The major suppliers of 1G wire are American Superconductor and Sumitomo Electric.
- 1G wire has been and is being investigated and tested for applications such as fault current limiters, transformers, MRI, maglev trains, specialty magnets and others.
- Due to the high price of wire, which is in the range of $100-150/kA-m today, the market has not grown significantly.

# In recent years, a consensus has developed around the need to move to 2G wire to meet price and performance targets necessary for HTS device commercialization.

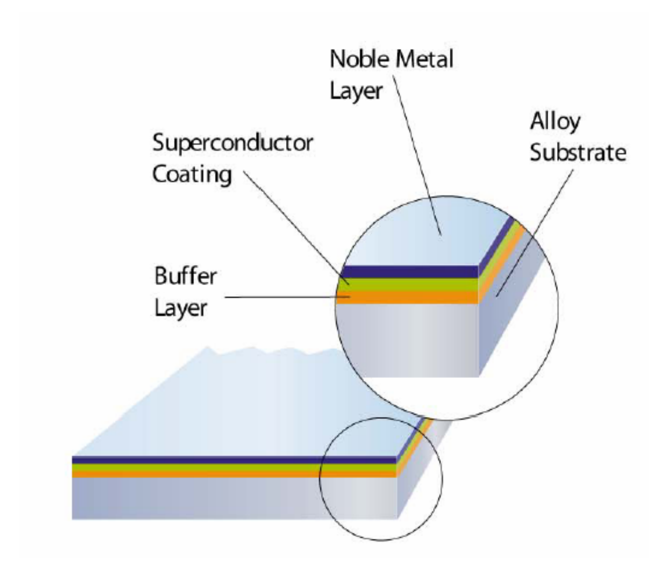
- **1G (BSSCO) wire will likely not meet the price and performance goals because:**
  - its high silver content will continue to make it too expensive to compete on price against copper;
  - its critical current density is too low due to poor grain alignment; and,
  - its performance in high fields is insufficient for some applications.

# In an effort to reduce cost, YBCO-based 2G wire is made in layers with a drastically reduced silver content.

**2G (YBCO) could achieve cost and performance goals because:**

- the materials cost is lower, using far less silver than 1G wire;
- the layered structure is better suited to longer manufacturing runs and higher process throughput;
- its in-field performance appears to be adequate for use in electric power applications; and
- with continued development, AC losses appear acceptable for use in electric power applications.

2G YBCO Wire



Source: American Superconductor

**Good YBCO grain alignment is critical to achieving high critical current densities, and has been a priority of wire R&D.**

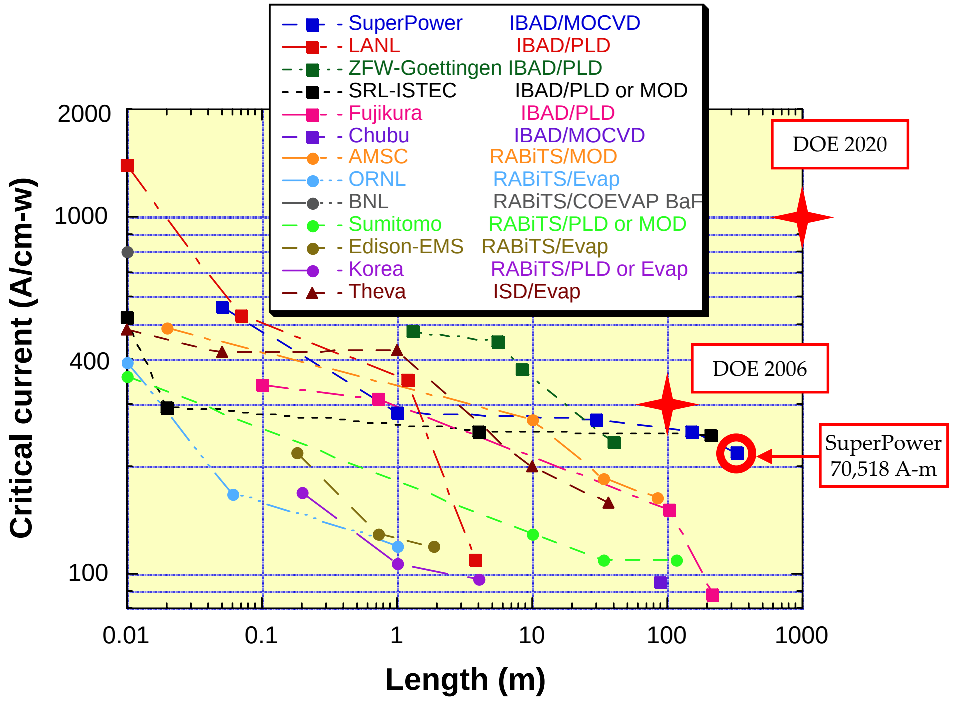
# Two manufacturing approaches, IBAD and RABiTS, are being developed to enable good grain alignment of the YBCO superconductor.

| | **IBAD/MOCVD**<br>**(Ion Beam Assisted Deposition / Metal Oxide Chemical Vapor Deposition)** | **RABiTS/MOD**<br>**(Rolling-Assisted Biaxially Textured Substrate/ Metal-Organic Deposition)** |
|---|---|---|
| **Process Description** | As a buffer layer is deposited on a substrate, an ion beam is directed at the growing layer producing a specific crystalline orientation. The oriented buffer layer provides the template for the YBCO which is deposited using a metal oxide chemical vapor deposition process. | A substrate is mechanically textured to create a grain alignment template for the buffer and YBCO. The YBCO deposited using a metal-organic deposition process. |
| **Long Samples (July 2006)** | 322 meters @ 219 A/cm | 94 meters @ 350 A/cm |
| **Short Samples (July 2006)** | 464 A/cm | 508 A/cm |
| **Scale-up Focus** | High linear tape speeds using multi-pass helical tape handling with tape slit to standard width | Wide tape that is slit to standard width (currently 4cm with plans for 10cm) |
| **Wire Research Lead** | **Los Alamos National Laboratory**<br>Provides significant support to SuperPower through DOE CRADA programs for additional wire development to assist with manufacturing scale up | **Oak Ridge National Laboratory**<br>Provides significant support to AMSC through DOE CRADA programs for additional wire development to assist with manufacturing scale-up |
| **Commercialization Lead** | **IGC SuperPower**<br>Has selected IBAD under a non-exclusive license from LANL, and has several patents for process optimization. | **American Superconductor**<br>Has applied the RABiTS approach under a non-exclusive license from ORNL, and has several patents related to process optimization. |

**Both approaches are designed to increase critical current density and in-field performance through good grain alignment in the YBCO.**

# In May 2006, DOE's 2006 goal of 30 kA-m was exceeded as SuperPower achieved over 70 kA-m with a tape sample over 300 meters long.

HTS wire performance has exceeded DOE goals for FY 2006



Source: Los Alamos National Laboratory, June 2006

**DOE HTS Performance Goals**
**Critical Current × Length**

| Year | kA-m |
|---|---|
| 2006 | 30 |
| 2007 | 40 |
| 2008 | 50 |
| 2010 | 70 |
| 2012 | 100 |
| 2014 | 500 |
| 2015 | 800 |
| 2020 | 1,000 |

Source: DOE

- The 2006 kA-m goal was surpassed, and researchers and wire manufactures continue to increase critical current and tape length
- Progress toward price and production goals will be critical to demonstrations, and the ultimate success of the technology in the coming years.

# Wire performance and price requirements vary by application, and will drive the timing of market entry.

**Industry Consensus Wire Performance Requirements for Various Utility Device Applications**

| **Application** | **$J_c$ (Acm$^{-2}$)** | **Field (T)** | **Temp. (K)** | **$I_c$ (A)** | **Wire Length (m)*** | **Strain (%)** | **Bend Radius (m)** | **Cost ($/kA- m)*** |
|---|---|---|---|---|---|---|---|---|
| Power Cable (transmission) | >$10^5$ | 0.15 | 67-77 | 200 A, 77 K, sf | >500 | 0.4 | 2 (cable) | 10-50 |
| Synchronous Condenser | $10^5$‡ | 2-3‡ | 30-77‡ | 100-500‡ | >1,000‡ | 0.2‡ | 0.1‡ | 30-70‡ |
| Fault Current Limiter | $10^4$-$10^5$ | 0.1-3 | 70-77 | 300‡ | >1,000 | 0.2 | 0.1 | 30-70‡ |
| Large Industrial Motor (1,000 hp) | $10^5$ | 4-5 | 30-77 | 100-500 | >1,000 | 0.2-0.3 | 0.1 | 10-25‡ |
| Utility Generator | $J_e$ >$10^4$ | 2-3 | 50-65 | 125 at $T_{op}$ , 3 T | >1,000 | 0.4-0.5 | 0.1 | 5-10 |
| Transformer | $J_c$ >$10^6$<br>$J_e$ >12,500 | 0.15 | 70-77 | >100<br>@ 0.15 T | >1,000 | 0.3 | 0.05 | 10-25‡ |

Original Data R. Blaugher, et. al., Updated by Gouge, Ashworth – January, 2006,

*Wire mfg, some equipment mfg indicate shorter length is adequate for early applications

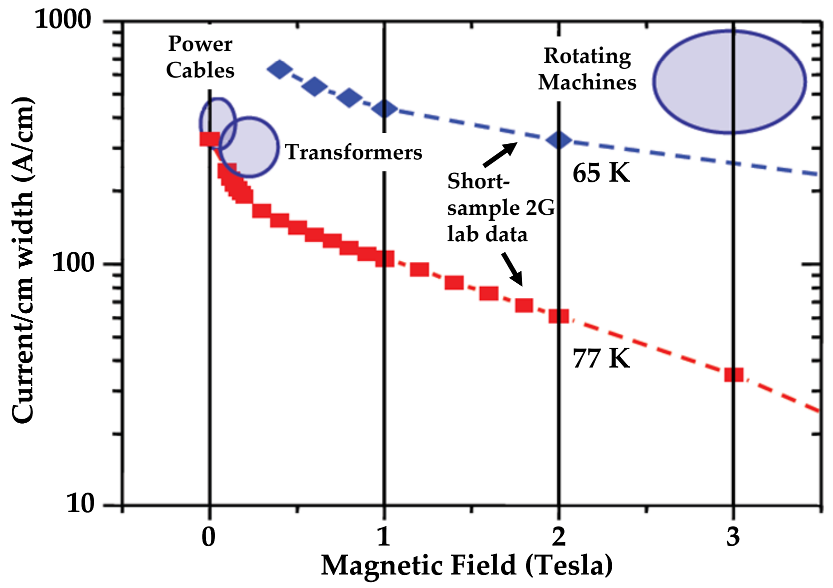
‡ Based on NCI assessment

*Cost target for a commercial market to develop. Target cost of wire is likely to be higher today due to rising price of copper and other materials.

# Today, 2G wire is close to meeting the critical current and in-field performance requirements for some applications.

- Current and magnetic field requirements are close to being met for certain applications in laboratory samples.
- The next step will be proving that these results can be achieved in manufacturing conditions and in long lengths.
- Meanwhile, achieving higher currents at high magnetic fields (2 to 4 T) requires additional breakthroughs or a colder operating environment.

**Short samples of 2G wire are nearly meeting performance requirements for some applications**



Source: Daley, James G. "Research Needs for HTS Power Delivery Technology." January 31, 2006. http://www.energetics.com/meetings/wire06/pdfs/session1/daley.pdf

# Once a marginal level of performance is achieved by HTS wire, demonstration devices can be built, but the cost-performance ratio must be reduced for market entry and commercialization.

| Technology Attributes | Near-Term Goals (present – 2007) | Mid-Term Goals (2008 – 2011) | Long-Term Goals (2012 – 2015) |
|---|---|---|---|
| **Critical current** | 250 A/cm, 77 K, sf<br>125 A/cm, 65 K, 2 T | 500 A/cm, 77 K, sf<br>250 A/cm, 65 K, 2 T | 1000 A/cm, 77 K, sf<br>500 A/cm, 65 K, 2 T |
| **Cost/Performance Ratio** | $400/kA-m, 77 K, sf<br>$800/kA-m, 65 K, 2 T | $50/kA-m, 77 K, sf<br>$100/kA-m, 65 K, 2 T | $10/kA-m, 77 K, sf<br>$20/kA-m, 65 K, 2 T |
| **Wire Length** | 100 m | 1000 m | >1000 m |
| **AC Losses** | 1 – 2 W/m | 0.5 – 1.0 W/m | < 0.50 W/m |

Source: NCI Analysis, Southwire, DOE.

# Cryogenics reliability and cost are critical elements in the ultimate success and market penetration of HTS technology.

- Cryogenics costs are a significant share of total HTS system cost, and will limit the market as a result
- Systems for larger cable projects can be designed today to be highly reliable, but effective business models for service must be developed
- More efficient and cost effective cryocoolers are critical to the value proposition for HTS applications
- Advanced technology cryocoolers need to be scaled up to larger sizes and the efficiency and reliability needs to be proven
- Application-specific, optimized cryostats are also critical, and their development is needed for cable and other applications.

**Pulse Tube Cryocoolers**

Source: SHI Cryogenics Group

# Efficiency, reliability and cost of cryogenics are important components of life cycle cost for an HTS device; improving these factors will increase the likelihood HTS devices will be commercially successful.

| Technology Attributes | | Near-Term Goals (present – 2007) | Mid-Term Goals (2008 – 2011) | Long-Term Goals (2012 – 2015) |
|---|---|---|---|---|
| **Cryogenics** | **Carnot Efficiency** | 12% @ 65 K | 20% @ 65 K | 30% @ 65 K |
| | **Reliability** | 95% | 99% | > 99.9% |
| | **Cost** | $100/W @ 65K | $60/W @ 65K | $25/W @ 65K |
| **Cable Cryostats*** | **Heat Leak** | 2 W/m | 1 W/m | < 0.5 W/m |
| | **Cost** | $500/m | $300/m | $100/m |

* Heat leak and cost goals apply to cryostats for the power cable application.
Source: NCI Analysis, Southwire, DOE.

# Dielectrics have performed sufficiently for some applications, but improvements in materials and designs appear necessary for others.

- Experience with dielectrics has been mixed, and in some cases has been the source of major technical problems in previous demonstrations.
- Most experience has been adopted from traditional dielectric approaches in oil filled or solid dielectric devices, with very little focus on cold system dielectrics.
- The use of cryogenic cooling fluids (i.e. $LN_2$) as a dielectric material, especially in high voltage environments and under all operating conditions (transient, fault, etc…) must be thoroughly investigated.
- While some research has been done in this area, the ultimate success of HTS technology depends heavily on dielectric systems designed to operate in cryogenic environments

# These are several HTS technology and systems-level challenges toward achieving successful device commercialization.

| Application | Critical HTS Technology Challenges | Critical Engineering / Application Challenges |
|---|---|---|
| **Power Cable** | • Reduce heat leak from the cryostat, improve efficiency of cryogenics, reduce AC losses, improve cost-performance ratio of HTS wire<br>• Simpler, more robust and cost effective cryostat designs | • System reliability, splices, designs for low maintenance<br>• Thermal and hydraulic issues over long lengths, fault current tolerance<br>• Business models for cryocooler maintenance |
| **Synchronous Condenser** | • Improve cost-performance ratio of HTS wire at field | •Optimization for application, larger sizes |
| **Fault Current Limiter** | • Understand quench characteristics at high voltages and currents | • Electro-mechanical design requirements, cycling characteristics, device lifetime |
| **Industrial Motor** | • Improve cost-performance ratio of HTS wire at field, improve performance of cryogenics | • System reliability, low cost packaged system |
| **Utility Generator** | • Improve cost-performance ratio of HTS wire at field, identify suitable dielectric materials, improve cryogenics | • Going to larger sizes, system reliability, low cost packaged system |
| **Wind Generator** | • Improve cost-performance ratio of HTS wire at field, improve cryogenics | • Small and lightweight, larger sizes, design challenges in offshore marine environment |
| **Transformer** | • Reduce AC losses, improve cost-performance ratio of HTS wire, identify suitable dielectric materials | • Larger sizes, low cost packaged system, system reliability<br>• Develop load tap changing technology |

# Several R&D initiatives are being pursued to improve wire performance and reduce cost.

| Technology Platform | Research Initiative | National Labs | Wire Mfgs |
|---|---|---|---|
| **Wire** | Increase critical current ($I_c$) | Lead | Support |
| | Improve in-field performance ($J_c$) | Lead | Support |
| | Increase engineering current density ($J_e$) for applications | Support | Support |
| | Reduce AC losses | Lead | Support |
| | Improve uniformity of wire in long lengths | Support | Lead |
| | Develop in-situ monitoring and QC methods | Support | Lead |
| | Reduce the number of buffer layers | Lead | Support |
| | Reduce wire manufacturing cost | Support | Lead |
| | Increase wire production and throughput | Support | Lead |

# R&D initiatives to improve cryogenics and dielectrics are being led by industry, with some support from the Labs, but more is needed.

| Technology Platform | Research Initiative | National Labs | Industry |
|---|---|---|---|
| **Cryogenics** | Increase efficiency of cryogenics | Support | Lead |
| | Increase reliability of cryogenics | Support | Lead |
| | Lower cost of cryogenics | | Lead |
| **Dielectrics** | Testing dielectric materials in cryogenic and high voltage environments | Support | Lead |

# The HTS program currently has a significant level of early stage R&D on conductor and balance of system components.

| | Examples of HTS Project Areas | | |
|---|---|---|---|
| | **Discovery Research** | **Targeted Research and Development** | **Technology Maturation and Deployment** |
| **Conductor Research (Wire Technology)** | • Magnetic flux pinning<br>• Control of nanodefects & interfaces<br>• Higher Tc superconductivity<br>• Multilayers/Buffers | • Near-isotropic high-pinning superconductors | • Isotropic YBCO superconductor |
| **Conductor Research (Wire Manufacturing)** | • Filament Development<br>• Tape transposition<br>• Dielectric architecture<br>• HTS film deposition rate >100 m/hr of 1,000 A/cm tape | • 1,000 A/cm width at 77K<br>• Kilometer lengths<br>• Production rate 10,000 km/yr | • 2nd Generation Wire Manufacture <$50/kA-m |
| **SPI (Devices, Applications, & Balance of System)** | • High voltage dielectrics | • Cryorefrigeration<br>• Pre-commercial high-efficiency superconducting power delivery systems | • Prototype motors, generators, transformers, FCL devices based on 2G wire |

***As currently funded, the DOE program does not support all areas requiring development***

# During 2006/2007, three major cable demonstration projects are scheduled to be energized.

**Three cable projects will be energized in 2006/2007**

| Project | Description and Status |
|---|---|
| **Albany, NY<br>SuperPower/ National Grid** | • 3-phase, 48 MVA – 34.5 kV, 800 A, 350 m<br>• Phase I - 77 km 1G HTS wire for a 350 m cable, Phase II - 9.7 km 2G HTS wire for 30 m cable segment<br>• Bi-2223 wire and cable supplied by Sumitomo, cryogenics by BOC,<br>• YBCO to be supplied by SuperPower<br>• Phase I Operational Summer 2006, Phase II - YBCO Cable installation and commissioning Summer '07 |
| **Columbus, OH<br>Ultera/AEP** | • 3-phase, 69 MVA – 13.2 kV, 3,000 A, 200 m<br>• Single core cable, cold dielectric<br>• Underground cable w/multiple 90 degree bends, joined in underground vault, built in field<br>• 1G HTS wire supplied by AMSC, cryogenics provided by Praxair<br>• Planning to be in service for normal operation in Fall 2006 |
| **Long Island, NY<br>AMSC/LIPA** | • 3-phase, 574 MVA – 138 kV, 2,400 A, 610 m<br>• 155 km of 1G HTS wire<br>• 1G HTS wire supplied by AMSC, cryostat supplied by Nexans<br>• Cryogenic system designed and managed by AMSC<br>• Currently planning to be energized in Summer 2007 |

# There have been some highly successful recent demonstration projects that support the potential of HTS devices.

| There have been several successful HTS demonstrations | |
|---|---|
| **Project** | **Description and Key Features** |
| **Carrollton Cable**<br>**Southwire** | • 30 m of HTS cable (AMSC 1G wire) to power Southwire's Carrollton complex<br>• 3 single phase cables capable of carrying 1250 A (AC) at 12.4 kV<br>• Operated successfully >38,000 hours at 100% load, over a period of six years.<br>• Cryogenics support provided by Praxair and have operated over 2 years successfully. |
| **Industrial Motor**<br>**Rockwell/AMSC**<br>**(2000)** | • 1000 HP industrial motor<br>• Motor developed by Rockwell with AMSC 1G wire<br>• Partners: Air Products and Chemicals and First Energy also provided support. |
| **Navy Motor**<br>**Navy/AMSC**<br>**(2003)** | • 5 MW prototype of marine propulsion motor for a Navy application<br>• 36.5 MW propulsion motor contract awarded to AMSC in 2004 |
| **SuperVAR**<br>**TVA/AMSC**<br>**(2004)** | • First major grid demonstration of a HTS synchronous condenser ("SuperVAR")<br>• 8 MVAR unit operating at 13.8 kV to support transient voltage loads at a steel mill<br>• Unit experienced over 5 million events and successfully demonstrated capability during 2000 on-line hours of operation. |

# However, there have been some major failures which underlie the risk associated with technology demonstrations.

**HTS demonstrations have shown that technical challenges still exist**

| Project | Description and Key Features | Failure Mechanism |
|---|---|---|
| **HTS Cable DTE/Pirelli** | • First major US HTS cable project<br>• AMSC provided 1G HTS wire, Pirelli Cable provided the Cryostat and was the project manager | • Cryostat leakage and other technical and quality problems plagued the project<br>• Never energized |
| **HTS Transformer Waukesha/ SuperPower** | • 10 MVA transformer | • Dielectric failed at 1 kV and project never brought up to full power |
| **Matrix Fault Current Limiter SuperPower** | • This project suffered major failures when undergoing component testing that resulted in the project being stopped before full testing. | • Failure of melt-cast BSCCO tubes with high current testing<br>• Never subjected to full testing |
| **Motor Rockwell** | • 1000 HP motor demonstration | • Rotor windings failed undergoing a quench |

**Project failures have not been the result of 1G wire technology, but instead the failure of ancillary technologies/systems.**

# It has also been concluded that more design reviews (readiness reviews), would benefit the industry.

- Readiness Reviews were initiated in 2003 as a means of more effectively identifying major areas of risk in projects, developing plans for risk mitigation and sharing experience and lessons learned throughout the industry.
- Important issues that have been a focus of the readiness reviews are:
    - Fault currents in cables
    - Thermal contraction of cables
    - Cryostats (mostly focused on cables)
    - High voltage, dielectric materials
    - Quenching in HTS coils
- Everyone interviewed by NCI has indicated that the readiness reviews have been very beneficial and will increase the likelihood of success of the next round of projects.
- The current approach using 3 Phases of reviews appears to be adequate for addressing these needs going forward.

# Table of Contents

# NCI has analyzed the key issues facing HTS to assess the technology and its ability to support commercial markets.

## The Technology

**Can HTS technology be developed to provide a compelling set of benefits for important market applications?**

- Are the market requirements for technology performance and price well understood?
- Can HTS technology meet any of these targets today?
- Can HTS technology be improved to meet some or all of these targets in the future?
- Do we understand the resource requirements for improving HTS technology to meet the market requirements?
- Does the HTS community believe that the desired results can be achieved?
- Do we understand how long it will take to improve HTS technology to meet the market requirements?

## The Market

**Can attractive markets be developed by leveraging the benefits of HTS technologies?**

- Are there market segments that could benefit from a technology offering higher capacity, higher efficiency, smaller size, or lighter weight?
- Could the benefits of HTS create new applications built on the value it provides?
- Do we understand how long it will take to develop market applications for HTS to a significant size?
- Does HTS technology offer a compelling value proposition for capturing a significant share of these markets in a reasonable timeframe?

# The most important near term energy and utility markets appear to be fault current limiters and synchronous condensers.

- Due to the relative clarity and strength of their value propositions, the strongest early markets for HTS are likely to be fault current limiters and synchronous condensers. Mass markets such as cable, transformers and generators that value low impedance and energy density will emerge much later.
- New applications in energy and utilities are likely to value the small and light characteristics such as off-shore wind turbines. Other new applications may emerge when there is more opportunity to experiment with the technology.
- We do not fully understand how long it will take to develop these markets, but it is likely to take 5-10 years of niche applications and experimentation in most segments before broader, mass markets develop.
- It is not clear today if HTS offers a compelling value proposition in many of the important applications that will demand higher volumes of wire and as a result more application studies, demonstrations and government support will be required to develop these markets.

***It is likely to take 5-10 years of application studies, experimentation and demonstrations before broader markets develop.***

# There are many potential applications for HTS. Each potential application will utilize the unique performance attributes of HTS.

**Examples of Potential HTS Applications**

| Utility/ Energy | Weapons/ Defense | Transportation | Industrial | Medical/ Health | Science |
|---|---|---|---|---|---|
| • **Power Cables**<br>• **Synchronous Condensers**<br>• **Fault Current Limiters**<br>• **Utility Generators**<br>• **Wind Generators**<br>• **Transformers** | • Degaussing Cable<br>• Navy propulsion motors<br>• Reduced antenna length for submarines<br>• "E-bombs" (EMP)<br>• Directed energy weapons | • MAGLEV<br>• Marine propulsion<br>• Railroad engine applications | • **Industrial motors (> 1000 hp)** for process industry<br>• Magnetic separation<br>• Construction/ mining equipment | • Magnetic Resonance Imaging (MRI) | • High field magnets<br>• Current leads |

*Focus of this report*

# Market segments that assign the highest value to performance attributes are likely to be the best early markets for HTS.

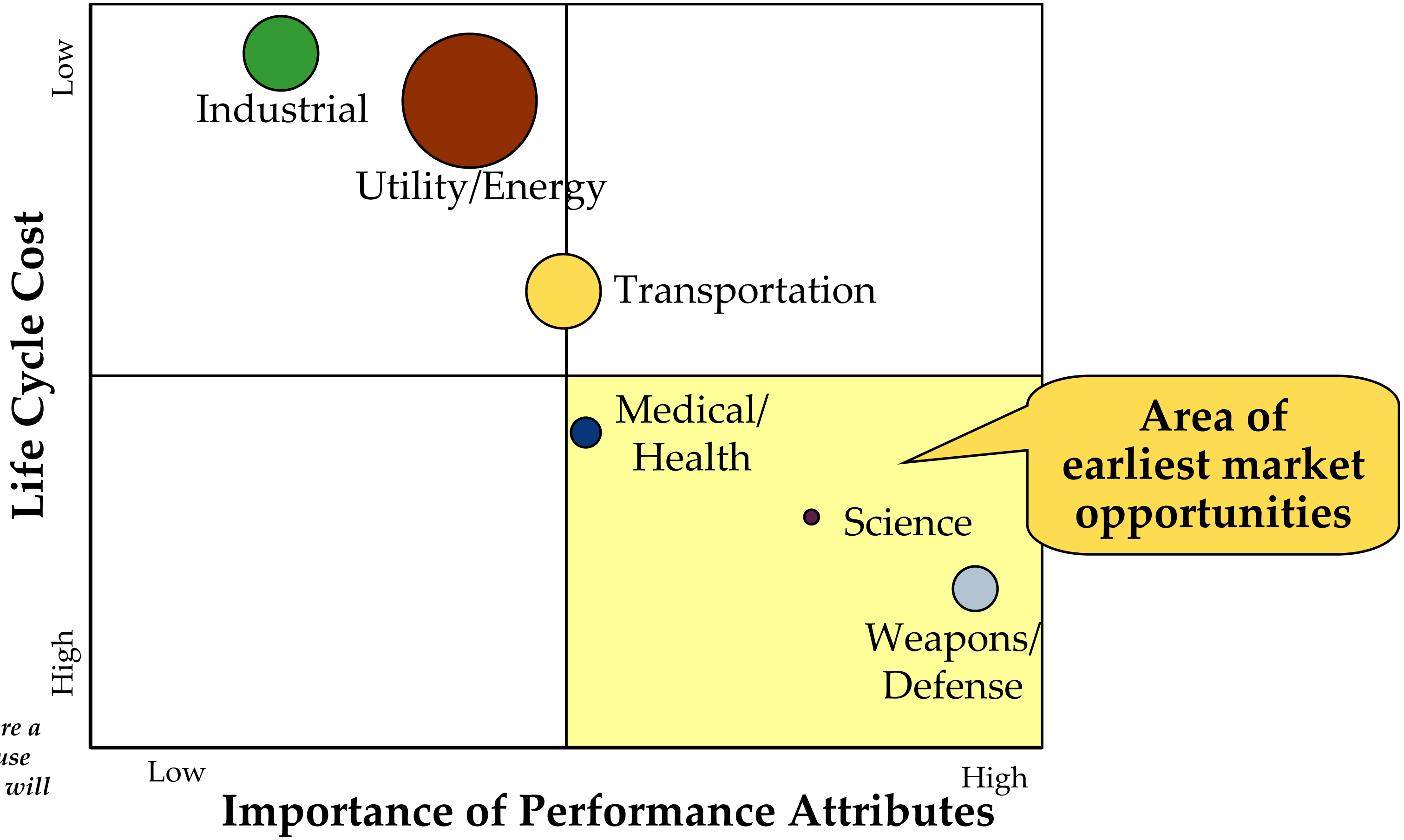
| | Importance of Performance Attributes | | | | | |
|---|---|---|---|---|---|---|
| | Small & Light | High Power Density | Low Impedance | High Efficiency | High Field | Overall |
| **Utility/Energy** | ◍ | ◍ | 🔵 | 🔵 | 🔵 | ◍ |
| **Weapons/Defense** | ● | ● | 🔵 | 🔵 | ● | ● |
| **Transportation** | 🔵 | 🔵 | 🔵 | 🔵 | 🔵 | 🔵 |
| **Industrial** | ◍ | ◍ | 🔵 | 🔵 | 🔵 | ◍ |
| **Medical/Health** | ● | ● | ◍ | ◍ | ● | 🔵 |
| **Science** | ◍ | 🔵 | ○ | ○ | ● | 🔵 |

Source: NCI Analysis

○ ◍ 🔵 ●

**Weak** ⇔ **Strong**

# In addition to assigning high value to HTS attributes, it is likely that market segments such as Defense and possibly Science may be prepared to pay the most for the technology.



*Note: Applications where a government is the end-use customer, life cycle costs will be less important.*

Note: The size of the ball denotes approximate market size.

# The Utility/Energy market may be largest long-term opportunity, but will require HTS sales from other segments to drive improvements in the cost-performance ratio before 2020.

| | Time Frame | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2006 | 2010 | 2014 | 2018 | 2022 | 2026 | 2030 |
| **Utility/Energy** | | | ○ | ○ | 🔵 | 🔵 | ● |
| **Weapons/Defense** | | ○ | ○ | ○ | ○ | ○ | ○ |
| **Transportation** | | | ○ | ○ | ○ | ○ | 🔵 |
| **Industrial** | | | | ○ | ○ | ○ | 🔵 |
| **Medical/Health** | | | | ○ | ○ | ○ | ○ |
| **Science** | | ○ | ○ | ○ | ○ | ○ | ○ |

Source: NCI Analysis

○ 🔵 ●
→
**Est. HTS Wire Sales**

# HTS technology offers significant benefits over a broad range of applications from power cables to advanced wind generators.

| Application | Primary Benefit | Secondary Benefits | Main Weaknesses | Competing Technologies |
|---|---|---|---|---|
| **Power Cable** | •High power at lower voltages than conventional solutions | •Power flow control<br>•No EMF outside cable | •Higher first cost and maint<br>•AC losses | •EHV OH transmission<br>•HS-LS conductor |
| **Synchronous Condenser** | •Best dynamic MVAR source<br>•Rotating inertia | •Overload capability<br>•No harmonic filtering | •First cost compared to SVC<br>•Experience with cryogenics | •D-VAR, Statcom, SVC |
| **Fault Current Limiter** | •Cost effective alternative to breaker upgrades | •Higher efficiency than other solutions | •Recovery under load and reclosing | •Larger circuit breaker (80kA)<br>•SS-FCL breaker |
| **Industrial Motors (>1000 hp)** | •Lower losses (50% for 1G motors, >50% 2G) | •Reduced weight and size | •Higher starting and fault currents | •Induction; permanent magnet |
| **Utility Generator (>300 MW)** | •Higher efficiency | •Better transient performance | •First cost<br>•Maintenance cost | •Primary: air cooled<br>•Secondary: gas/liquid cooled |
| **Wind Generator (5-10 MW)** | •Smaller size and lower weight mean higher output | •Eliminates gearbox<br>•Higher output voltage | •First cost<br>•Maintenance cost | •Conventional synchronous generators |
| **Transformer** | •Overload rating and reliability | •Environmental mitigation; Fire safety<br>•Size and weight | •Cost<br>•Maintenance | •No direct competition at this time |

Source: NCI Analysis, see Appendix: Value Propositions

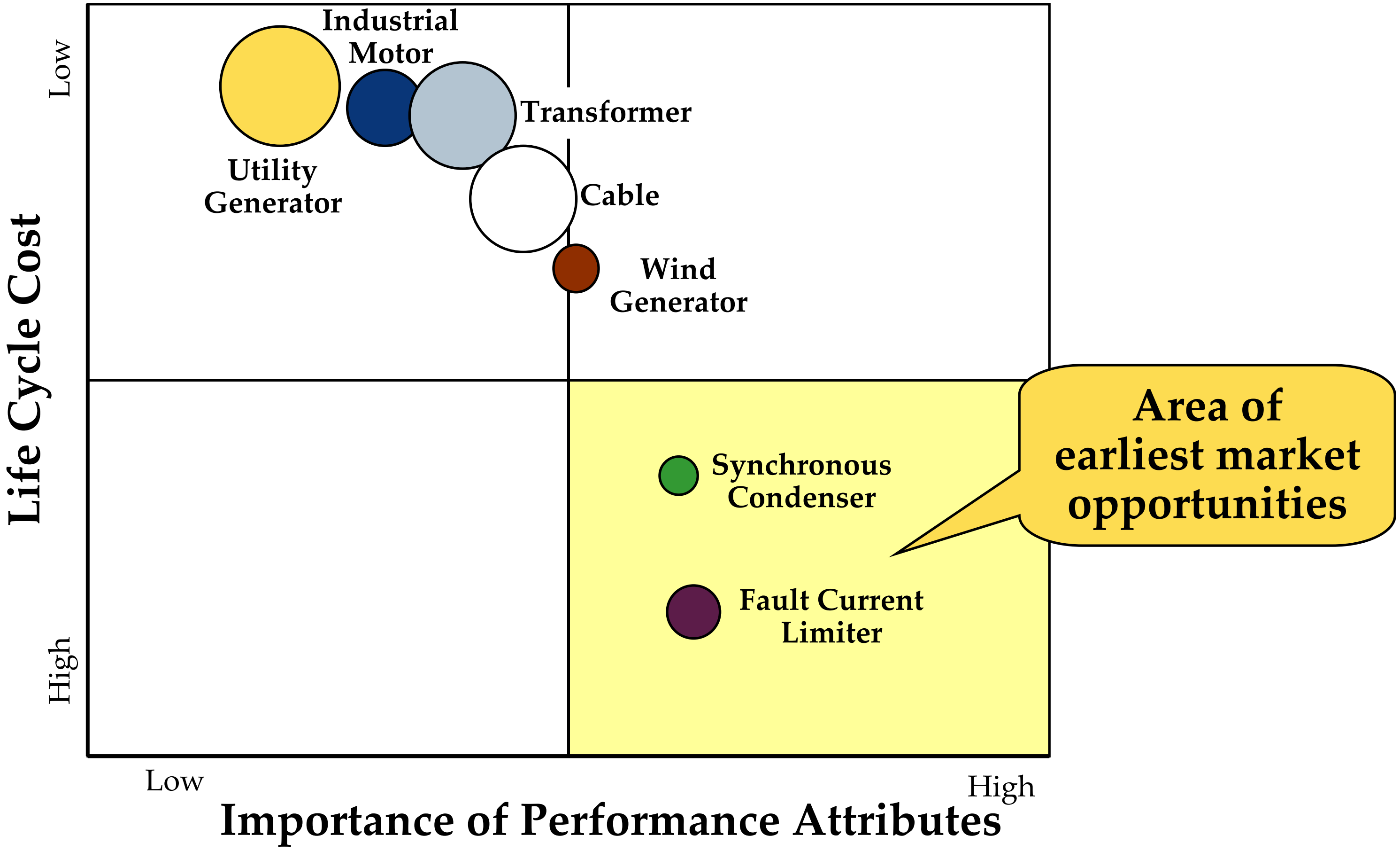
# In the utility/energy market, the applications that appear to value performance attributes of HTS most are Fault Current Limiters and Synchronous Condensers.

| | Utility/Energy Market - Importance of Performance Attributes | | | | | |
|---|---|---|---|---|---|---|
| | Small & Light | High Power Density | Low Impedance | High Efficiency | High Field | Overall |
| **Power Cable** | ◍ | ● | 🔵 | 🔵 | ○ | 🔵 |
| **Synchronous Condenser** | ◍ | ◍ | ● | ● | 🔵 | ● |
| **Fault Current Limiter*** | ◍ | 🔵 | 🔵 | ● | ○ | ● |
| **Industrial Motor** | ◍ | 🔵 | ◍ | ● | 🔵 | ◍ |
| **Utility Generator** | ○ | ○ | ● | ● | 🔵 | ◍ |
| **Wind Generator** | ● | 🔵 | ◍ | ◍ | 🔵 | 🔵 |
| **Transformer** | ◍ | 🔵 | ● | ● | ○ | ◍ |

Source: NCI Analysis, see Appendix: Value Propositions
* Fault current limiters also rely on the inherent quench properties of HTS.

⬜ ▨ 🟦 ⬛
**Weak** ⟺ **Strong**

# In the utility/energy market the majority of potential applications value low life cycle costs more than specific performance attributes.



Note: The size of the ball denotes approximate market size.

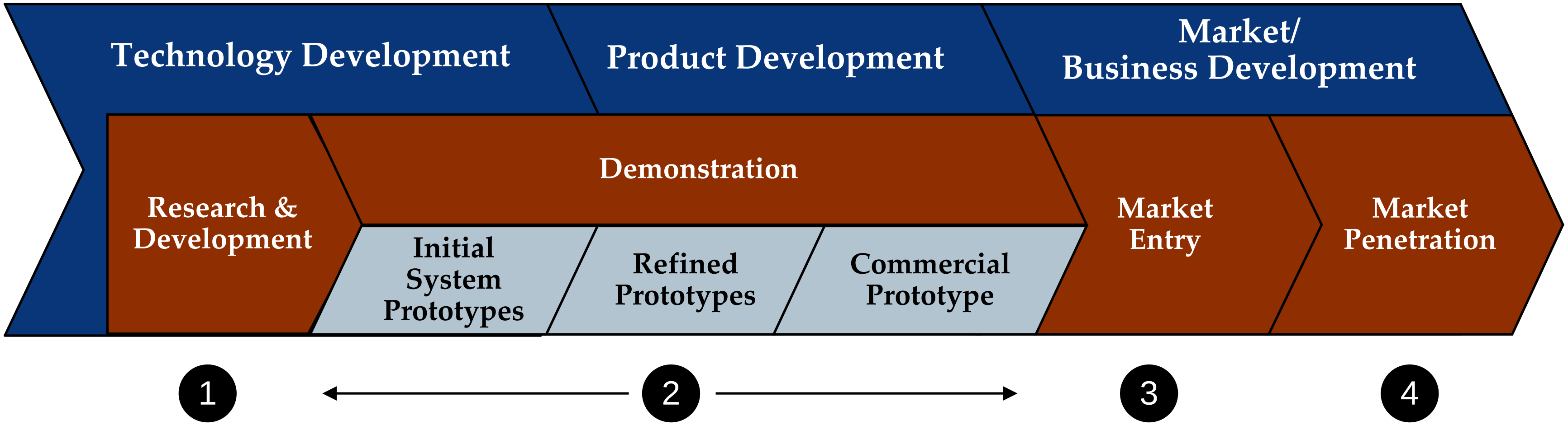
# Forecasted dates of market entry are strongly dependent on the status of the HTS technology platforms, but must also consider the success of demonstration projects and the strength of the value proposition.

| | Utility/Energy Market - Technology Attribute | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Wire | | | | Dielectrics | Cryogenics | | Cryostats | | |
| | Critical Current | Cost/ Performance Ratio | Wire Length | AC Losses | Performance | Carnot Efficiency | Reliability/ Cost | Heat Leak | Cost | Est. Date of Market Entry** |
| **Power Cable** | ⚪ | ⚫ | 🔵 | 🔵 | ⚪ | ⚫ | ⚫ | ⚫ | ⚫ | 2014 |
| **Synchronous Condenser** | 🔵 | 🔵 | 🔵 | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | 2011 |
| **Fault Current Limiter** | ⚪ | 🔵 | ⚪ | ⚪ | 🔵 | ⚪ | ⚪ | ⚪ | ⚪ | 2014 |
| **Ind. Motor** | 🔵 | ⚫ | ⚪ | ⚪ | ⚪ | 🔵 | 🔵 | ⚪ | ⚪ | 2016 |
| **Utility Generator** | 🔵 | ⚫ | 🔵 | ⚪ | ⚫ | 🔵 | 🔵 | ⚪ | ⚪ | 2020 |
| **Wind Generator** | 🔵 | 🔵 | 🔵 | ⚪ | 🔵 | 🔵 | 🔵 | ⚪ | ⚪ | 2014 |
| **Transformer (Med. / Large)** | 🔵/🔵 | ⚪/⚪ | 🔵/🔵 | ⚫/⚫ | 🔵/⚫ | 🔵/🔵 | 🔵/🔵 | ⚪/⚪ | ⚪/⚪ | 2014/17 |

** The forecasted date of market entry considers technology status, past demonstration projects, and the strength of the value proposition.
Note: The technology development status corresponds to the near-, mid- and long-term goals identified in the HTS Technology Platform section.

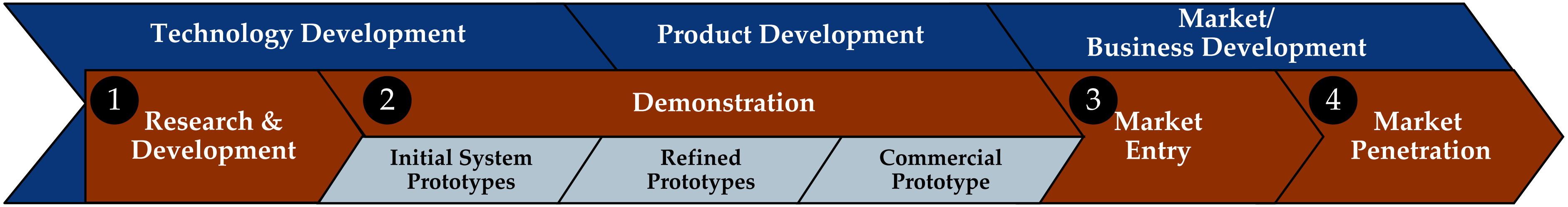
⚪ 🔵 ⚫ →
Near Mid Long

# Effective technology commercialization strategies require successfully completing the four product stages below.



Although there may be feedback to earlier stages, generally, these stages must occur in sequence, and individual stages should not be skipped in an attempt to accelerate the process.

# For each HTS application NCI used the technology commercialization framework to forecast market entry.



Technology Development

Product Development

Market/ Business Development

1 Research & Development

2 Demonstration

Initial System Prototypes

Refined Prototypes

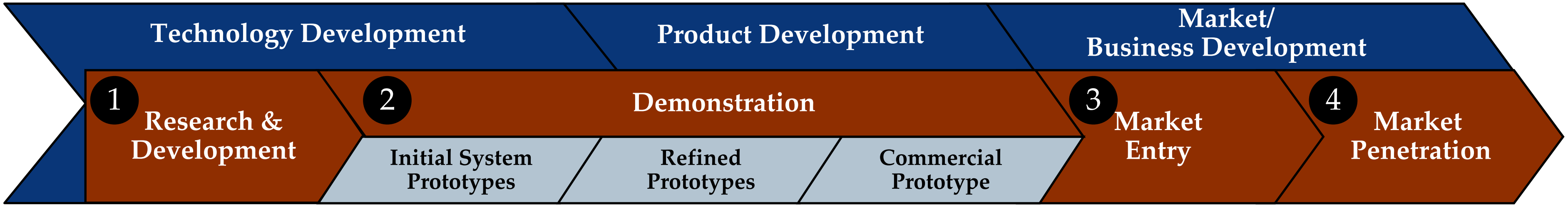
Commercial Prototype

3 Market Entry

4 Market Penetration

| | | | | | | |
|---|---|---|---|---|---|---|
| **Description of Typical Activities** | •Research on component technologies<br>•General assessment of market needs and product specifications<br>•General magnitude of economics | •Initial system prototypes for debugging | •Ongoing development to reduce costs or for other needed improvements | •Full size system in "commercial" operating environment<br>•Communicate program results to early adopters/selected niches | •Initial commercial orders<br>•Early movers or niche segments<br>•Product reputation is initially established<br>•Business concept implemented | •Follow-up orders based on need and product reputation<br>•Broad(er) market penetration<br>•Infrastructure developed<br>•Full-scale manufacturing |
| **Key Transition Factors** | •Major technical issues identified and solutions defined<br>•Adequate info to define system<br>•Clear path to acceptable economics<br>•Performance acceptable with market needs<br>•Initial estimates of market size and attractiveness | •All major system components prototyped<br>•Basic functionality demonstrated | •Requirements for commercial scale system understood<br>•Demonstrated progress towards cost/performance goals<br>•System capability matched to customer needs | •System demo in full commercial operation (size, continuous operation, real world)<br>•Demonstrate that future economics are attractive and adequate market size<br>•Reasonable match to market needs<br>•Acceptable market and technical risk/uncertainty<br>•Market attractiveness consistent with manufacturer investment | •Successful operation in varied applications (technical risk)<br>•Economic hurdle for widespread markets achievable<br>•Market size and needs exceed hurdle<br>•Market attractiveness consistent with manufacturer investment | •Market share established<br>•Sales growth rate achieved<br>•Broad-based markets |

# For example, HTS cables are likely to enter the market on a commercial basis around 2014, after additional demonstration stages.



| ongoing | 2005 | 2008 | 2011 | 2014 | 2017 |
|---|---|---|---|---|---|
| •Understand major technical issues, demonstrate key technical concepts<br>•Develop solutions to major technical issues<br>•Define system requirements<br>**Project Examples**<br>•DTE Cable Project<br>•Southwire Carrollton Project | •Initial system prototypes using 1G HTS wire<br>•Debug components<br>•Demonstrate technology in field environment.<br>**Project Examples**<br>•Southwire/AEP<br>•LIPA/AMSC<br>•Albany/ SuperPower | •Refine initial system with experience from prototypes<br>•Demonstrate value proposition in the field<br>**Projects**<br>•Full scale demonstration using 2G wire<br>•Full functionality<br>•Progress toward cost goals for major components | •Full size system in "commercial" operating environment<br>•Demonstrate future economics, acceptable market and technical risk<br>•Gov. support for industry standards<br>**Projects**<br>•Commercial cable project without backup option | •Formal business model<br>•Early movers<br>•Demonstrate value for broader market opportunities<br>**Projects**<br>•Customer driven cable project, without government support | •Market penetration accelerates<br>•Focus on lowering system costs<br>•Increasing diversity of product offerings |

# NCI projected the technology commercialization timeline for other utility/energy HTS applications.

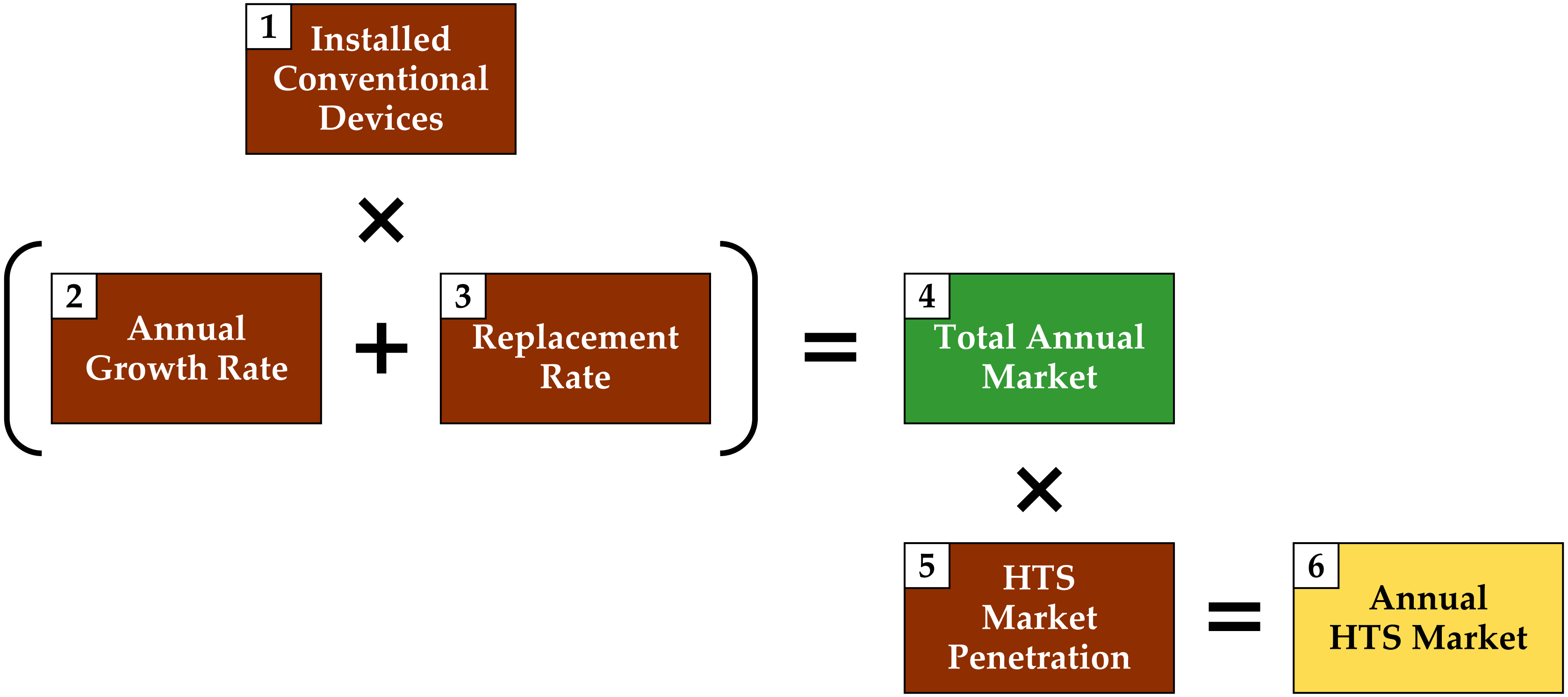
| | Technology Development | | Product Development | | Market/ Business Development | |
|---|---|---|---|---|---|---|
| | 1 Research & Development | 2 Demonstration | | | 3 Market Entry | 4 Market Penetration |
| | | Initial System Prototypes | Refined Prototypes | Commercial Prototype | | |
| **Power Cable** | ongoing | 2006 | 2008 | 2011 | 2014 | 2017 |
| **Synchronous Condensers** | ongoing | 2004 | 2006 | 2009 | 2011 | 2014 |
| **Fault Current Limiter** | ongoing | 2007 | 2010 | 2012 | 2014 | 2017 |
| **Industrial Motors** | ongoing | 2004 | 2006 | 2011 | 2016 | 2019 |
| **Utility Generators** | ongoing | 2008 | 2012 | 2016 | 2020 | 2023 |
| **Wind Generator** | ongoing | 2008 | 2010 | 2012 | 2014 | 2017 |
| **Transformers** | ongoing | 2003 | 2008 | 2011 | 2014 | 2017 |

Source: NCI Analysis, see Appendix: Technology Commercialization Timeline

# NCI created a detailed market model for three scenarios forecasting the long term potential of HTS devices, based on the technology commercialization assumptions developed during the study.

- The following market model assumes that DOE continues to support the development of HTS technology at or above the current levels.
- It has also been assumed that as soon as HTS wire technology is developed that will support the performance required for particular devices and applications that development of these devices is pursued.
- We have also assumed that the various devices are successfully developed over timeframes considered reasonable for power equipment of this type.
- The resulting model portrays three scenarios; a high, medium and low case, all of which assume that HTS devices are developed on the same timeframe.
  - The differences in assumptions used for the three scenarios relate to the following three areas, which are described in more detail in the appendix.
    - Power demand growth rates and growth rates for the markets for the various devices.
    - Market penetration rates for new technologies, and ultimate market shares for new technologies.

# NCI used a market penetration model to estimate when and how many HTS devices will penetrate their respective markets.



1 Installed Conventional Devices

×

( 2 Annual Growth Rate + 3 Replacement Rate ) = 4 Total Annual Market

×

5 HTS Market Penetration = 6 Annual HTS Market

*The objective of this analysis is to estimate the potential size of the HTS market.*

# For each HTS market segment, NCI developed a market penetration model based on industry interviews and a literature review.

| | |
|---|---|
| **1 Installed Conventional Devices** | • The size of the market that HTS devices will enter is a key factor for forecasting the size of the HTS market. |
| **2 Annual Growth Rate** | • The annual growth rate determines the number of new installations each year. |
| **3 Replacement Rate** | • The replacement rate determines the number of new devices that replace existing devices. |
| **4 Total Annual Market** | • The annual market is the sum of devices attributed to market growth and the replacement market. |
| **5 HTS Market Penetration** | • Certain technology and industry factors are used to estimate when HTS market entry will occur and the rate of HTS technology adoption. |
| **6 Annual HTS Market** | • The annual HTS market is the product of the total addressable market and the HTS market penetration rate. |

Additional details about the model are located in the Appendix.

# The size of the US market for utility/energy devices in all scenarios is considerably smaller than the ROW market.

| | Low Scenario | | Medium Scenario | | High Scenario | |
|---|---|---|---|---|---|---|
| | Addressable Market in 2030 | HTS Market in 2030 | Addressable Market in 2030 | HTS Market in 2030 | Addressable Market in 2030 | HTS Market in 2030 |
| **Power Cable (miles)** | 236 | 23 | 316 | 78 | 409 | 204 |
| **Synchronous Condensers (25 MVA)** | 14 | 2 | 17 | 8 | 20 | 10 |
| **Fault Current Limiter (unit)** | 258 | 25 | 304 | 150 | 355 | 177 |
| **Industrial Motors (5000 hp)** | 23 | 0 | 106 | 25 | 215 | 107 |
| **Utility Generators (300 MW)** | 22 | 0 | 35 | 4 | 51 | 25 |
| **Wind Generator (5 MW)** | 94 | 14 | 160 | 79 | 303 | 227 |
| **Medium Transformers (30 MVA)** | 1,506 | 71 | 1,933 | 476 | 2,432 | 608 |
| **Large Transformers (300 MVA)** | 139 | 0 | 178 | 40 | 225 | 112 |

# The ROW market for HTS utility/energy devices is larger than the US market as the infrastructure in the ROW must keep up with growing demand.

| | **Low Scenario** | | **Medium Scenario** | | **High Scenario** | |
|---|---|---|---|---|---|---|
| | **Addressable Market in 2030** | **HTS Market in 2030** | **Addressable Market in 2030** | **HTS Market in 2030** | **Addressable Market in 2030** | **HTS Market in 2030** |
| **Power Cable (miles)** | 1,563 | 149 | 2,285 | 563 | 3,217 | 1,608 |
| **Synchronous Condensers (25 MVA)** | 66 | 10 | 105 | 52 | 151 | 75 |
| **Fault Current Limiter (unit)** | 1,271 | 121 | 1,632 | 805 | 2,068 | 1,034 |
| **Industrial Motors (5000 hp)** | 1,409 | 29 | 2,179 | 514 | 3,183 | 1,589 |
| **Utility Generators (300 MW)** | 187 | 0 | 383 | 48 | 626 | 303 |
| **Wind Generator (5 MW)** | 281 | 43 | 481 | 237 | 909 | 681 |
| **Medium Transformers (30 MVA)** | 9,149 | 434 | 12,989 | 3,201 | 17,919 | 4,479 |
| **Large Transformers (300 MVA)** | 845 | 2 | 1,199 | 268 | 1,654 | 825 |

# The Medium scenario is our best estimate of the HTS market, in terms of market timing and market size.

| | Low Scenario | | Medium Scenario | | High Scenario | |
|---|---|---|---|---|---|---|
| | Addressable Market in 2030 | HTS Market in 2030 | Addressable Market in 2030 | HTS Market in 2030 | Addressable Market in 2030 | HTS Market in 2030 |
| **Power Cable (miles)** | 1,799 | 172 | 2,600 | 641 | 3,626 | 1,813 |
| **Synchronous Condensers (25 MVA)** | 80 | 12 | 121 | 58 | 171 | 82 |
| **Fault Current Limiter (unit)** | 1,529 | 146 | 1,936 | 954 | 2,422 | 1,211 |
| **Industrial Motors (5000 hp)** | 1,431 | 29 | 2,285 | 539 | 3,398 | 1,697 |
| **Utility Generators (300 MW)** | 209 | 0 | 418 | 52 | 677 | 327 |
| **Wind Generator (5 MW)** | 374 | 58 | 642 | 316 | 1,212 | 908 |
| **Medium Transformers (30 MVA)** | 10,655 | 506 | 14,922 | 3,678 | 20,351 | 5,087 |
| **Large Transformers (300 MVA)** | 984 | 2 | 1,377 | 307 | 1,879 | 937 |

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# HTS AC cables provide high power density for constrained rights of way.

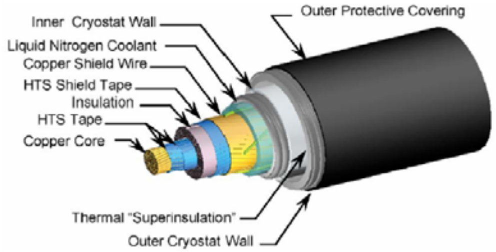
**Summary Value Proposition**
Provides the highest power density of any technology, except for HTS cable operated at DC. Cables are being designed to be direct buried in narrow rights of way, or to be direct replacements in existing duct banks, reducing space and permitting requirements. In addition, HTS cable will avoid thermal backfill associated with thermal management of conventional underground cable.

**Characteristics of HTS Technology in Application**

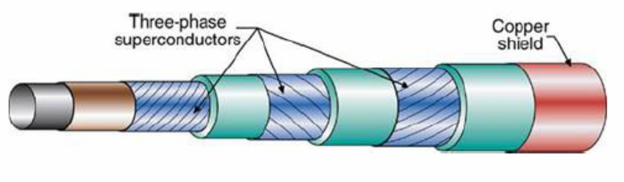
- Higher current carrying capacity through a smaller right of way (3 to 5 times that of conventional technology)
- Higher electrical efficiency than conventional technologies
- Very low impedance (VLI) of cable (very low resistance due to superconductive wire, low reactance due to compact geometry)
- Very low to no electromagnetic field outside cable due to concentric neutral. Triaxial cable configuration has all three phases and the neutral in a concentric design
- Eliminates the use of oil in some conventional cables
- AC losses of up to 3 Watts per meter of cable with current HTS, requires significant cooling, and limits power transfer capability.

**Situations Where Application Could be Attractive**

- Cables can be retrofit into existing ductwork to dramatically increase capacity – convert conventional "distribution" lines to "transmission" lines
- High capacity substation connection or "bus extension" into load centers in highly dense areas
- VLI cable could be used with a phase angle regulator (PAR) to control power flow



Source: US DOE



Source: Ultera

| | |
|---|---|
| Primary Benefit | • Higher power density, and high capacity at lower AC voltage, in some cases enabling transmission capacity at distribution voltage |
| Secondary Benefits | • Flexibility in locating capacity/source<br>• Power flow control with VLI cable/PAR<br>• Low or no EMF outside cable |
| Main Weaknesses | • Higher cost<br>• AC losses<br>• Higher maintenance |
| Competing Technologies | • Conventional EHV OH transmission<br>• Conventional UG transmission<br>• OH high-strength, low-sag conductor |

# HTS cables can deliver higher power through smaller rights of way than conventional alternatives.

| Attribute | AC | | | |
|---|---|---|---|---|
| | HTS Cable | OH ACSR | OH HTLS | UG XLPE/OF |
| **Installed Cost** | High | Low | Low | High |
| **Current Carrying Capacity** | High | Medium | High | Medium |
| **Right of Way** | Small | Large | Large | Medium |
| **Losses** | Low | Medium | High | Medium |
| **EMF** | Low | High | High | Medium |
| **Impedance** | Low | High | High | Medium |

# However, the high cost of HTS cable requires that significant value be derived from other benefits.

OH ACSR = Overhead Aluminum Conductor Steel Reinforced
OH HSLS = Overhead High Temperature Low Sag
XLPE/OF = Cross-Linked Polyethylene / Oil Filled

# An HTS synchronous condenser will provide cost competitive, voltage and transient stability support with early production 2G wire.

**Summary Value Proposition**

An HTS synchronous condenser (HTSSC) with 1G wire is currently available for purchase for voltage stability, transient stability, and industrial power quality , (flicker) applications with 1G wire at ~$150/kAm. Two additional units will be shipped to TVA for voltage support at an industrial customer, and according to the manufacturer additional applications are in discussion. With 2G wire and $I_c$ ~1000 A/cm width and costs <$35/kAm, the HTSSC could produce dynamic reactive compensation that is competitive with SVCs and in large sizes may be competitive with capacitors plus reactors.

**Characteristics of HTS Technology in Application**

- Competitive in $/kVAr now with STATCOMs and D-VARs, and eventually with SVCs, and even with capacitors plus reactors with 2G wire.
- Potential for high reliability (>99%) like any generator compared to <99% for D-VAR$^{TM}$ and STATCOM
- Inertia provides some real power to allow control of transients (like flicker) and provide some short outage duration ride-through
- Low losses of 1.5% due to operation at distribution voltages of 13.4 kV to 24 kV (no intermediate transformer losses), high part load efficiency.
- 2.5X peak output during a transient at 50% voltage. Transient output increases with decrease in system voltage to 50% voltage sag. 4X output possible in ½ second with fast exciter lasting for seconds.
- The device can generate or absorb reactive power to increase service reliability and maximize transmission capacity

**Situations Where Application Could be Attractive**

- Located near industrial facilities with significant electrical loads due to large induction motors and arc furnaces that create reactive power and voltage swings
- Near long transmission lines that suffer from voltage drop and stability issues.
- Urban locations where there are power quality problems.

Source: TVA

| | |
|---|---|
| **Primary Benefit** | • Competitively priced voltage and transient stability support, even with depressed bus voltage<br>• Flicker control<br>• Exciter driven peak reserve output<br>• Mechanical inertia providing real power |
| **Secondary Benefits** | • High transient overload capability<br>• Harmonic filtering not required<br>• Low losses<br>• Lower thermal fatigue than conventional synchronous condensers |
| **Main Weaknesses** | • Cost compared to SVC<br>• Maintenance issues with Cryocooler (unfamiliar technology to utilities) |
| **Competing Technologies** | • Statcom<br>• D-VAR$^{TM}$<br>• SVC |

# HTS Synchronous Condensers appear to be a promising option for dynamic voltage regulation, which is increasingly important for ensuring grid reliability.

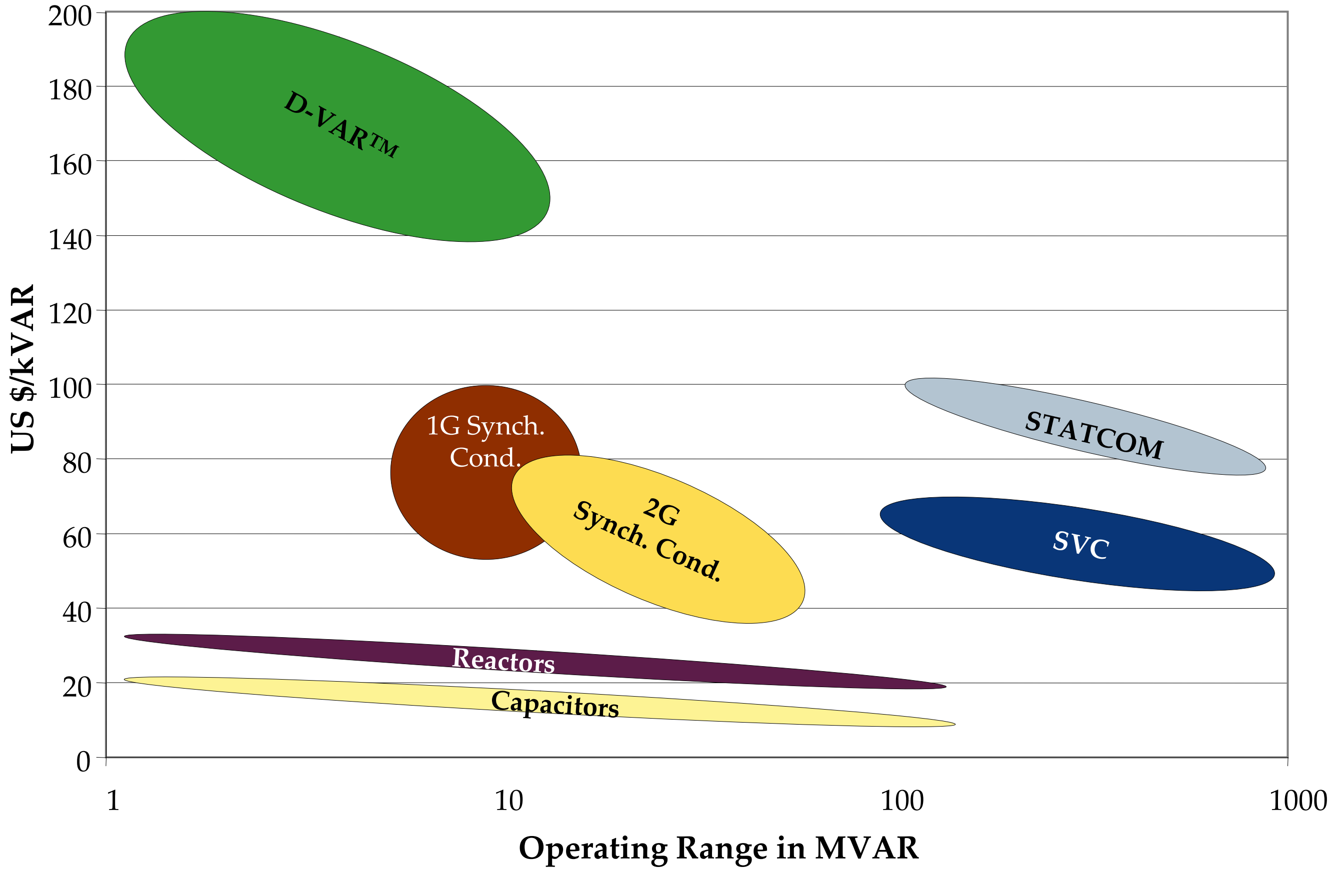
| Attribute | HTS Synchronous Condenser | Conventional Synchronous Condenser | D-VAR™ | StatCom* | SVC** | Capacitor |
|---|---|---|---|---|---|---|
| **Capital $/kVAR** | 100-110<br>(35-85 future) | 45-60 | 150-200 | 100-110 | 40-60 | 8-13 |
| **Operating Cost** | Medium | High | Medium | Medium | Medium | Low |
| **Size (footprint)** | Small | Large | Small | Medium | Large | Small |
| **Losses** | Low | Medium | Medium | Medium | Medium | Low |
| **Maintenance** | High | High | Medium | Medium | High | Low |
| **Speed of Response** | Instantaneous | Instantaneous | Fast | Fast | Fast | Slow/stepped |
| **Voltage Support** | Excellent | Excellent | Moderate | Moderate | Moderate | Poor |

*StatCom - Static Synchronous Compensator; regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system.

**SVC – Static VAr Compensator – Shunt device composed of capacitors and reactors

# On the basis of cost, SuperVAR™ appears to be very cost effective with other products, in addition to offering the other benefits.

## Average Cost of Reactive Power Technologies $/kVAR capacitance



# There are a broad range of static and dynamic reactive compensation devices available on the market today.

| Functional Characteristics | HTS Synchronous Condensers | D-VAR™ | STATCOM | SVC | Capacitors |
|---|---|---|---|---|---|
| **Solution Type** | Steady-state and Dynamic | Steady-state and Dynamic | Steady-state and Dynamic | Steady-state and Dynamic | Steady-state |
| **Range of Costs ($/kVAr capacitance)** | ***\$60 to \$100 (1G)***<br>***\$40 to 80 (2G)*** | \$150 to \$200 | \$110 to \$110 | \$40 to \$60 | ***\$8 to \$13*** |
| **Inherent Transient Overload Rating*** | ***Up to 4x nominal*** | 3x | Slight (1.25x) | No | No |
| **Real Power Output** | ***Seconds of real power using machine inertia*** | Optimal with SMES | None | None | None |
| **Losses**** | ***1.5%*** | 2.5% | 2.5% | 2.5% | ***1.0%*** |
| **Output Dependent on Bus Voltage** | ***Increases with voltage to 50%*** | Decreases linearly with voltage | Decreases linearly with voltage | Decreases with the square of voltage | Decreases with the square of the voltage |
| **Ease of Installation** | ***Simple*** | ***Simple*** | Complex | Complex | ***Simple*** |
| **Harmonic Compensation Required** | ***No*** | Application dependent | Yes | Yes | Application Dependent |
| **Response to severe (deep) voltage dips** | ***Sub-cycle*** | ***Sub-cycle*** | ***Sub-cycle*** | No | No |
| **Discrete Control of Output** | Slow (<1 sec) | ***Fast (1/4 cycle)*** | ***Fast (1/4 cycle)*** | ***Fast (1/4 cycle)*** | No |
| **Create Over Voltage Spikes** | ***No*** | ***No*** | ***No*** | ***No*** | Yes |

*SuperVAR™ instantly jumps to 2X at 50% V and begins to drop until the exciter kicks in and pushes the output to 4X
**losses includes losses of step up transformers

# Fault current limiters could defer expensive breaker upgrades.

**Summary Value Proposition**
A practical fault current limiter implemented at transmission voltage is one of the holy grails of electric power system engineering. As power systems become more highly networked and as more and more generation comes online, controlling fault current to within levels that existing equipment can tolerate is critical.

**Characteristics of HTS Technology in Application**

- Inherent quench characteristics of HTS material limit fault current while operating at very low loss under normal conditions
- 2G wire is better suited for this application: 1G wire quench is at 10 times Ic, while 2G wire quench is at 2-3 times Ic [1]
- Controls fault currents to levels that existing circuit breakers can operate
- Prevents equipment damage from high through fault currents, including transformers and cables

**Situations Where Application Could be Attractive**

- Avoid replacement of multiple circuit breakers of insufficient capability
- Locations where faults result in high circuit breaker maintenance or failure

Source: SuperPower

| | |
|---|---|
| Primary Benefit | • Limits fault current to levels that existing equipment can tolerate |
| Secondary Benefits | • Higher efficiency than conventional solutions |
| Main Weaknesses | • Recovery under load<br>• Reclosing |
| Competing Technologies | • Solid state fault current limiting breaker<br>• Vacuum fault interruptor |

---

1. Yi-Yuan Xie, SuperPower, 2G HTS Conductors for Fault Current Limiter Applications, 2006 HTS Wire Workshop

# Effective fault current control is one of the capabilities most eagerly awaited by utilities throughout the US.

| Attribute | HTS FCL | SSFCL CB* | 80 kA CB** |
|---|---|---|---|
| **Cost** | Very High | High | High |
| **Mode of Operation** | Limits current | Limits current | Interrupts current |
| **Electrical Efficiency** | High | Low | High |
| **Response Speed** | Sub-cycle | Sub-cycle | 2 cycles |
| **Physical Size** | Medium | Large | Large |
| **Maintenance** | High | Medium | Low |

*SSFCL CB – Solid State Fault Current Limiting Circuit Breaker

** 80 kA CB – Non-FCL, SF6 80 kA circuit breaker,

# HTS industrial motors will need to be competitively priced and provide a strong efficiency benefit in addition to high reliability.

**Summary Value Proposition**

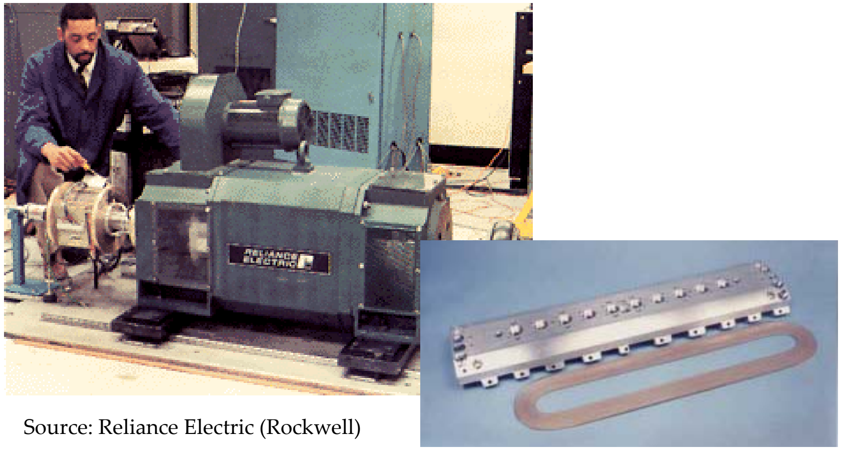
HTS industrial motors will have half the losses of industrial induction motors, have a smaller footprint and weight (which will reduce structural costs in new facilities). In new coal fired power plant applications that use motor driven boiler feed pumps, this could increase plant output and heat rate by 3% or more. Efficiency improvements in older coal fired units could be even greater.

**Characteristics of HTS Technology in Application**

- HTS motors will have 50% lower losses than new, high efficiency induction motors
- HTS motor economics for industrial application are sensitive to wire costs and are competitive when 2G wire costs are $10-35/kAm and when cryocooler costs are reduced from today
- Attractive for applications that value small and light characteristics – mining equipment, vertically installed pumps, compressors, and other applications where space and structural costs are an issue
- HTS motors can provide VArs depending on remote dispatch and exciter operation.

**Situations Where Application Could be Attractive**

- HTS motors could provide costs reductions for new PC w/FGD &SCR and IGCC by increasing output, reducing motor losses and improving heat rate, and reducing structural costs due to the lower weight and smaller size.
- Mining equipment where motor size is currently a constraint for equipment design.



Source: Reliance Electric (Rockwell)

| | |
|---|---|
| Primary Benefit | • 50% less losses for 1G motors and >50% less losses for all HTS 2G motors<br>• Capable of providing VArs depending on exciter operation while providing torque |
| Secondary Benefits | • Reduced weight and size resulting in reduced structural costs for new facilities |
| Main Weaknesses | • Higher in-rush currents during faults<br>• Increases system fault currents |
| Competing Technologies | • Induction motors |

# HTS motors offer significant reductions in size and weight, as well as gains in efficiency as compared to conventional motor technologies.

| Attribute | HTS Industrial Motors | Conventional Induction Motors | Conventional Synchronous Motors |
|---|---|---|---|
| **Cost** | High | Low | Medium |
| **Synchronous Reactance** | Low | Medium | Medium |
| **Total Harmonic Distortion** | Low | Medium | Medium |
| **Vibration and Noise** | Low | High | Medium |
| **Size/weight** | Small/Light | Large/Heavy | Large/Heavy |
| **Maintenance** | Low[1] | Medium | Medium |
| **Losses** | Low | High | Medium |

1 – Assuming Cryogenics are very reliable and low maintenance

# The best applications for HTS generators will be for >300 MW, baseload operation or smaller units for cogen or industrial plants.

**Summary Value Proposition**

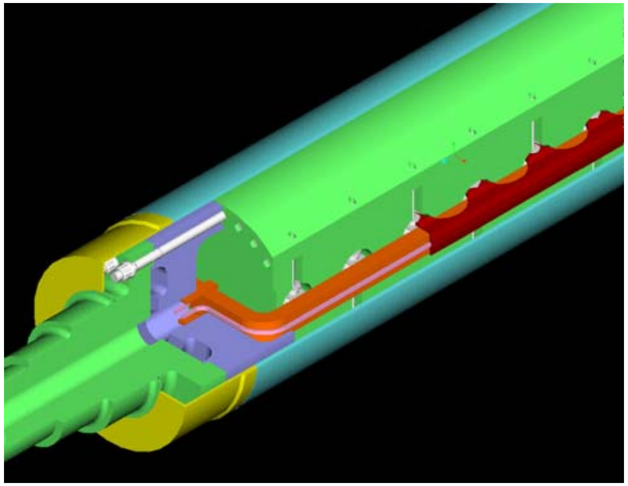
HTS generators for large coal and nuclear power plants will provide 0.5-1.0% lower losses than conventional hydrogen cooled generators used in these applications. For other baseload plant applications HTS generators may also be attractive due to lower losses. An additional benefit may be the ability to up-rate these generators more easily in the future, should there be opportunities. Reliability and life should be very attractive due to the cooled rotor and lack of thermal cycling.

**Characteristics of HTS Technology in Application**

- The generation system may save the cost and efficiency of a GSU transformer if the generator can be operated at a higher voltage. (Hull, 3)
- Reduced vibration and noise will be benefits as HTS systems have no iron teeth in the rotor or armature (AMSC, 1)
- Applications will need to target baseload power plants, where hydrogen cooled generators are used today. Will not be attractive where air cooled units are used.
- HTS generators will offer improved reliability by eliminating temperature fluctuations in rotor coils (Wolsky, GE)
- World total purchases of 60-100 generators per year in the 100 MVA to 400 MVA range and 100-150 units per year in the >500 (Wolsky, GE, NCI)

**Situations Where Application Could be Attractive**

- HTS generators will be attractive in new power plants where design features can be leveraged to lower other costs (e.g. elimination of GSU).



Source: General Electric

| | |
|---|---|
| Primary Benefit | • Higher efficiency than conventional H2 or air cooled generators |
| Secondary Benefits | • Higher output from an existing unit<br>• Better transient performance |
| Main Weaknesses | • First cost<br>• Maintenance cost |
| Competing Technologies | • Depending on size, can be hydrogen cooled, air cooled or gas and liquid cooled generators |

# Generators will benefit from lower electrical losses, leading to increased efficiency and output from a given plant.

| Attribute | HTS Generator | Conventional H2 Cooled | Conventional Air Cooled |
|---|---|---|---|
| **First Cost** | High | High | Medium |
| **Life Cycle Cost** | Medium | Medium | Medium |
| **Cycling Capability** | Poor | Moderate | Strong |
| **Size** | Medium | Large | Large |
| **Maintenance** | High | Medium | Low |
| **Losses** | Low | Medium/Low | Medium |

# Wind turbine generators may allow larger units than otherwise possible with conventional technology.

**Summary Value Proposition**

HTS generators for wind turbines would allow larger wind turbines for off-shore applications, because of their smaller size and lower weight.  This may allow wind turbine of 5-10 MW in size. Additional benefits may be possible when used in a DC application.

**Characteristics of HTS Technology in Application**

- The generation system may save the cost and efficiency of a GSU as the generator may be operated at a higher voltage. (Hull, 3)
- Reduced vibration and noise as HTS systems have no iron teeth in the rotor or armature (AMSC, 1)
- Improved reliability by eliminating temperature fluctuations in rotor coil (Wolsky, GE)
- World market for large wind turbines for off-shore applications is likely to exceed 5000 MW per year. Sales of units larger than 5 MW for off shore application could run 500-1000 per year within 10 years.
- Better reliability and lower maintenance with the elimination of the gearbox

**Situations Where Application Could be Attractive**

- Low speed, multi pole generators of 5-10 for deep water, off-shore wind farms may be an attractive application. Target areas with class 6 wind, and high capacity factor opportunities.

Source: **top left:** http://www.bbc.co.uk; **top right:** http://www.hornsrev.dk; **bottom:** http://www.nationmaster.com [eingesehen 03.08.2005]

| | |
|---|---|
| Primary Benefit | • Smaller size and lower weight will allow significantly higher output from existing towers |
| Secondary Benefits | • Ability to rotate more slowly may eliminate the need for a gearbox<br>• Higher operating voltage – no T/F |
| Main Weaknesses | • First cost<br>• Maintenance costs |
| Competing Technologies | • Conventional synchronous generators with gear boxes |

# The smaller size and weight of HTS generator may make an attractive market for offshore wind energy generators.

| Attribute | HTS Wind Generator | Conventional Wind Generator |
|---|---|---|
| **First Cost** | Higher | Lower |
| **Size** | Smaller | Larger |
| **Weight** | Lighter | Heavier |
| **Maintenance** | Lower | Higher |
| **Losses** | Lower | Higher |

# Efficiency, size and weight improvements for large HTS transformers could make them attractive for replacement high load growth areas.

**Summary Value Proposition**

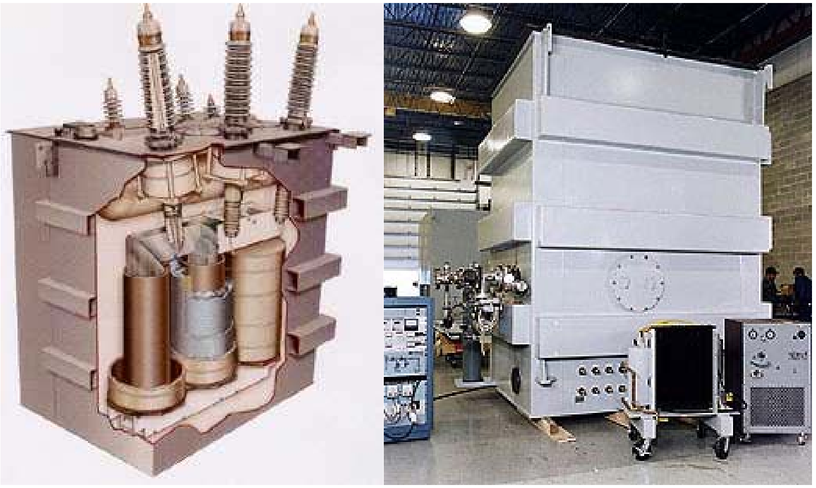
The HTS transformer's efficiency and reliability could offer utilities and generators life-cycle cost improvements and risk reduction. Overload performance and part-load efficiency could also offer utilities much needed flexibility for system operations and load growth. Smaller size and weight could enable a utility to quickly move units around to support greater energy security and reliability.

**Characteristics of HTS Technology in Application**

- 50% reduction in size and weight compared to conventional transformers due to the high power density of HTS wire (AMSC and Waukesha).
- Increased efficiency
- Higher reliability through the elimination of hotspots
- High overload capacity thermal management
- Elimination of oil and associated environmental and safety hazards
- Lower impedance (AMSC)
- Could be inherently fault current limiting with development

**Situations Where Application Could be Attractive**

- Generator step-up applications where higher efficiency and reliability means more MWh delivered to the market
- High growth areas, or areas with non-uniform load duration curves where part-load efficiency and overload performance could be valuable
- The overload rating, coupled with smaller size and lighter weight, could facilitate standardization on fewer sizes



Source: Intermagnetics General Corporation and Waukesha

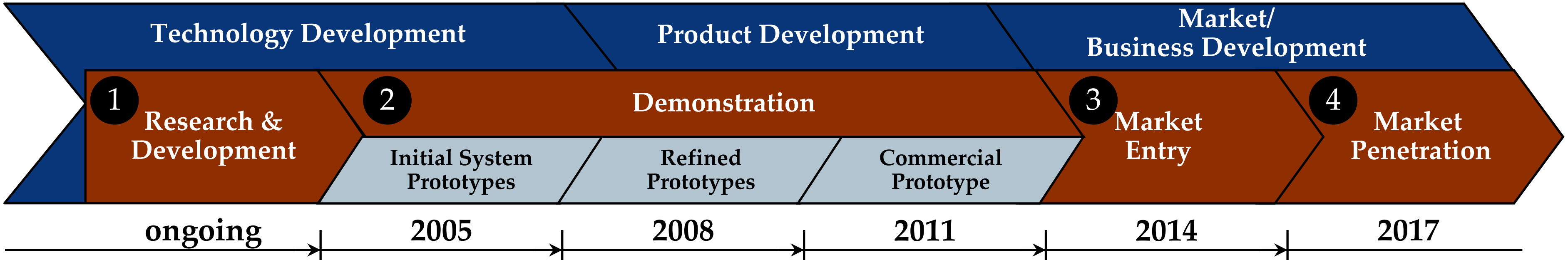
| | |
|---|---|
| Primary Benefit | • Higher efficiency and reliability |
| Secondary Benefits | • Fire safety<br>• Environmental mitigation costs<br>• Size and weight |
| Main Weaknesses | • Cost<br>• Maintenance |
| Competing Technologies | • No direct competition at this time |

# Increased efficiency for transformers, as well as short term overload capability make HTS attractive.

| Attribute | HTS Transformer | Conventional Transformer |
|---|---|---|
| **First Cost** | Higher | Lower |
| **Size** | Smaller | Larger |
| **Maintenance** | Higher | Lower |
| **Losses** | Lower | Higher |
| **Overload Rating** | Higher | Lower |
| **Fire Safety** | Better | Worse |
| **Environmental Mitigation** | Better | Worse |

## Table of Contents

# HTS cables are likely to enter the market on a commercial basis around 2013, but additional stages of demonstration will be required.



**Technology Development**

**Product Development**

**Market/ Business Development**

**1 Research & Development**

**2 Demonstration**

**Initial System Prototypes**

**Refined Prototypes**

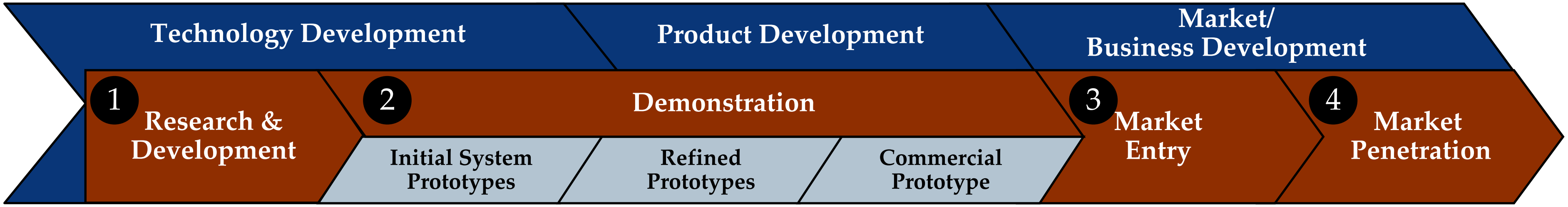
**Commercial Prototype**

**3 Market Entry**

**4 Market Penetration**

| ongoing | 2005 | 2008 | 2011 | 2014 | 2017 |
|---|---|---|---|---|---|
| •Understand major technical issues, demonstrate key technical concepts<br>•Develop solutions to major technical issues<br>•Define system requirements<br><br>**Project Examples**<br>•DTE Cable Project<br>•Southwire Carrollton Project | •Initial system prototypes using 1G HTS wire<br>•Debug components<br>•Demonstrate technology in field environment.<br><br>**Project Examples**<br>•Southwire/AEP<br>•LIPA/AMSC<br>•Albany/ SuperPower | •Refine initial system with experience from prototypes<br>•Demonstrate value proposition in the field<br><br>**Projects**<br>•Full scale demonstration using 2G wire<br>•Full functionality<br>•Progress toward cost goals for major components | •Full size system in "commercial" operating environment<br>•Demonstrate future economics, acceptable market and technical risk<br>•Gov. support for industry standards<br><br>**Projects**<br>•Commercial cable project without backup option | •Formal business model<br>•Early movers<br>•Demonstrate value for broader market opportunities<br><br>**Projects**<br>•Customer driven cable project, without government support | •Market penetration accelerates<br>•Focus on lowering system costs<br>•Increasing diversity of product offerings |

# An HTSSC was field tested at TVA in 2004-2005, and refined prototypes will be delivered to TVA in 2007.



Technology Development

Product Development

Market/ Business Development

1 Research & Development

2 Demonstration

Initial System Prototypes

Refined Prototypes

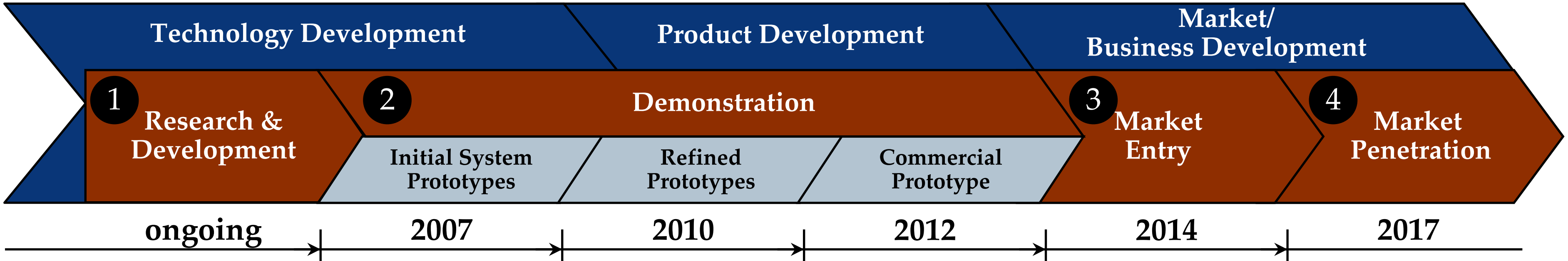
Commercial Prototype

3 Market Entry

4 Market Penetration

| ongoing | 2004 | 2006 | 2009 | 2011 | 2014 |
|---|---|---|---|---|---|
| •Understand major technical issues and develop solutions<br>•Test in controlled, lab environment.<br>•Define system requirements<br>**Project Examples**<br>•Rockwell/AMSC 1000 HP motor<br>•Rockwell/AMSC 1600 HP motor<br>•Rockwell 7.5 hp HTS motor w/2G | •Initial system prototypes<br>•Debug components<br>•Demonstrate technology in field<br>**Project Examples**<br>•AMSC demonstration at TVA of first 8 MVA HTSSC (SuperVAR$^{TM}$) | •Refine initial systems with experience from prototypes<br>•Demonstrate cost, and reliability and additional market value.<br>**Projects**<br>•12 MVA SuperVAR$^{TM}$ , 1G wire for TVA<br>•Additional applications under discussion | •Demonstrate additional market value<br>•Refine business model<br>**Projects**<br>•An HTSSC using 2G wire | •Formal business model<br>•Sales to early movers<br>•Demonstrate value for broader market | •Market penetration accelerates<br>•Full product line – 10-50 MVA – based on 2G wire<br>•Focus on lowering system cost |

# A transmission level FCL must be prototyped and demonstrated, and could enter the commercial market by 2013.



Technology Development

Product Development

Market/
Business Development

1 Research & Development

2 Demonstration

Initial System Prototypes

Refined Prototypes

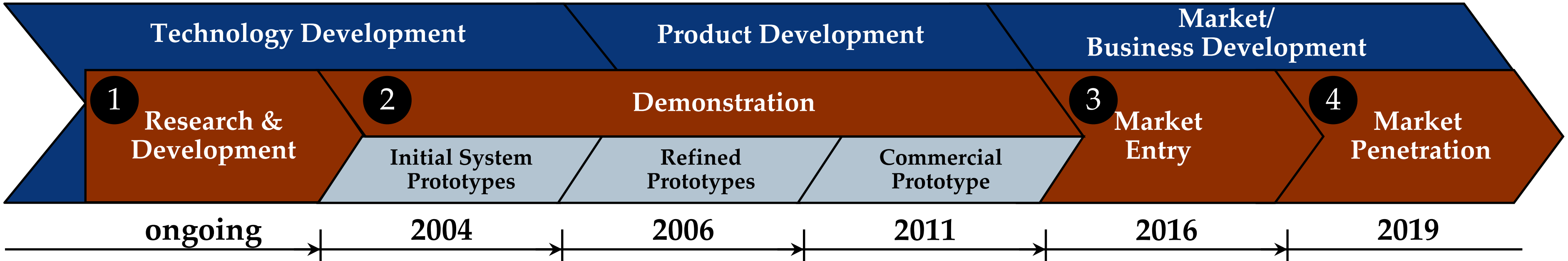
Commercial Prototype

3 Market Entry

4 Market Penetration

| ongoing | 2007 | 2010 | 2012 | 2014 | 2017 |
|---|---|---|---|---|---|
| •Understand major technical issues, Demonstrate key technical concepts<br>•Develop solutions to major technical issues<br>•Define system requirements<br>**Project Examples**<br>•July 2004: Proof-of-concept pre-prototype Matrix FCL (SuperPower)<br>•2007: Alpha prototype at 138 kV single phase (non-grid) | •Initial system prototypes, including new coil using 2G wire<br>•Debug components<br>•Demonstrate technology in field<br>**Project Examples**<br>•2007-08: Beta prototype at 138 kV 3-phase, in AEP system | •Refine initial system prototype<br>•May modify coil design, topology and control to improve response and recovery under load (RUL)<br>•Demonstrate value proposition<br>**Projects**<br>•Full scale demonstration<br>•Full functionality<br>•Progress toward cost goals for major components | •Full size system in “commercial” operating environment<br>•Demonstrate that future economics will be attractive<br>•Acceptable market and technical risk<br>**Projects**<br>•Commercial project without backup option | •Formal business model<br>•Early movers<br>•Demonstrate value for broader market<br>**Projects**<br>•Customer driven project, without government support | •Market penetration accelerates<br>•Focus on lowering system cost<br>•Increase diversity of product offerings |

# HTS industrial motors will require an extended period of prototype testing, benefiting from work on propulsion motors and SuperVar.



**ongoing**

- Understand major technical issues and develop solutions
- Test in controlled, lab environment.
- Define system requirements

**Project Examples**

- Rockwell/AMSC 1000 HP motor
- Rockwell/AMSC 1600 HP, 1800 RPM motor tested in 2001 w/1G
- Rockwell 7.5 hp, 1800 RPM motor tested in 2005 w/2G

**2004**

- Initial system prototypes
- Debug components
- Demonstrate technology in the field

**Project Examples**

- AMSC 3.5 MW motor
- AMSC 5 MW Navy Motor program
- AMSC/TVA 8 MVA SuperVar

**2006**

- Refine initial systems with experience from prototypes
- Demonstrate cost and reliability potential.

**Projects**

- Full scale (2000 hp) demo w/ full functionality
- Progress toward cost goals for components and 2G wire

**2011**

- Full size system in "commercial" operating environment
- Demonstrate future economics will be attractive
- Acceptable market and technical risk.

**Projects**

- Commercial project without backup option

**2016**

- Formal business model
- Early movers
- Demonstrate value for broader market

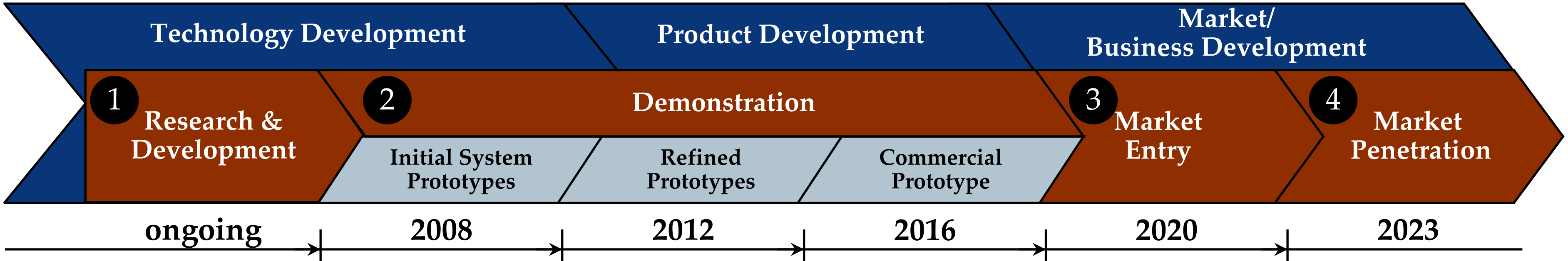
**Projects**

- Customer driven project, without government support

**2019**

- Market penetration accelerates
- Focus on lowering system cost
- Increase diversity of product offerings

# Large HTS Generators are not likely to receive much interest until 2G wire is mature and there is significant experience with other devices.



**Technology Development**

**Product Development**

**Market/ Business Development**

1 **Research & Development**

2 **Demonstration**

**Initial System Prototypes**

**Refined Prototypes**

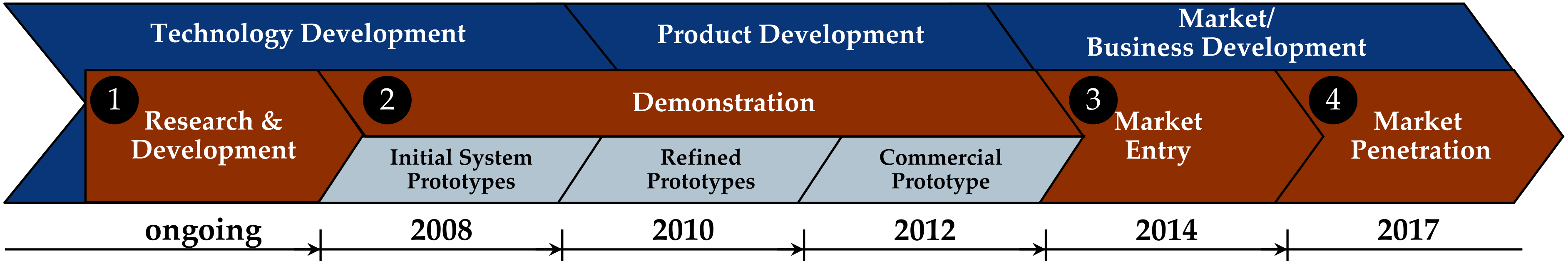
**Commercial Prototype**

3 **Market Entry**

4 **Market Penetration**

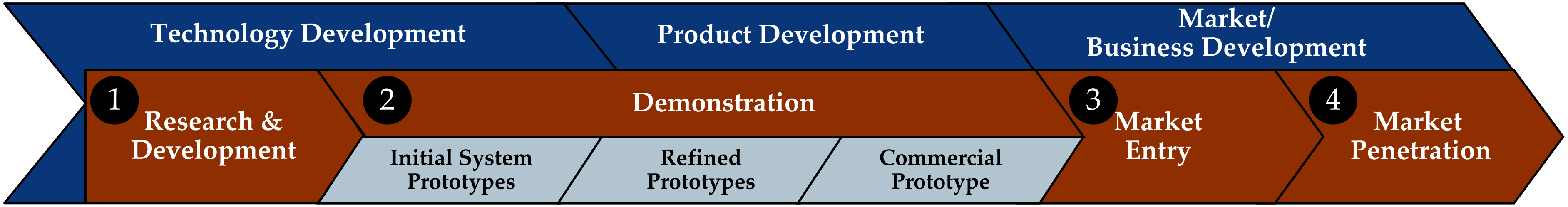
| ongoing | 2008 | 2012 | 2016 | 2020 | 2023 |
|---|---|---|---|---|---|
| •Understand major technical issues and develop solutions<br>•Tests in controlled lab environments.<br>•Studies to define system requirements<br>**Project Examples**<br>•GE Generator Program<br>•Military programs | •Develop scale prototypes<br>•Develop 2G wire for high field applications<br>•Assess cost and performance of components<br>**Projects**<br>•Testing of coils and components<br>•Verify 2G wire performance in high field | •Demonstrate cost and reliability potential smaller prototypes or experience from motors/ SuperVAR<br>**Projects**<br>•Demonstration of generator benefits, likely based on a smaller unit (< 50 MW) | •Full size system in "commercial" operating environment<br>•Demonstrate future economics will be attractive<br>•Acceptable market and technical risk.<br>**Projects**<br>•Full size generator project (>300 MW) | •Formal business model<br>•Early movers<br>•Demonstrate value for broader market<br>**Projects**<br>•Customer driven project, without government support or with limited government support. | •Market penetration accelerates<br>•Focus on lowering system cost |

# An HTS wind generator would require a new technology development initiative, but it would leverage other rotating machinery efforts.



| ongoing | 2008 | 2010 | 2012 | 2014 | 2017 |
|---|---|---|---|---|---|
| •Understand major technical issues and develop solutions<br>•Test in controlled lab environments<br>•Studies to define system requirements<br>**Project Examples**<br>•Feasibility studies<br>•Systems studies of off-shore wind | •Develop scale prototypes<br>•Develop 2G wire for high field applications<br>•Assess cost and performance benefits.<br>**Projects**<br>•Testing of coils and components<br>•Develop scale wind turbine and conduct testing | •Refine initial systems prototypes<br>•Demonstrate cost and reliability potential.<br>**Projects**<br>•Full scale (5-10 MW) demo w/ full functionality<br>•Progress toward cost goals for components and 2G wire | •Full size "commercial" system<br>•Demonstrate future economics will be attractive<br>•Acceptable market and technical risk.<br>**Projects**<br>•Commercial off-shore wind project, leverage government programs and incentives for renewable energy | •Formal business model<br>•Early movers<br>•Demonstrate value for broader market<br>**Projects**<br>•Customer driven projects, without government support | •Market penetration accelerates<br>•Driving toward lower system costs |

# HTS transformers will require improvements in the performance and cost of HTS wire before they can enter the commercial market in 2014.



| ongoing | 2003 | 2008 | 2011 | 2014 | 2017 |
|---|---|---|---|---|---|
| •Understand major technical issues, Demonstrate key technical concepts<br>•Develop solutions to major technical issues<br>•Define system requirements<br>**Project Examples**<br>•1997: Phase I, 1 MVA HTS transformer tested developed and tested (Waukesha and SuperPower) | •Initial system prototypes, including new coil using 2G wire<br>•Debug components<br>•Demonstrate technology in field<br>**Project Examples**<br>•2003: Phase II, 5/10 MVA Alpha prototype developed and tested (Waukesha and SuperPower) | •Refine initial system prototypes<br>•Demonstrate value proposition<br>**Projects**<br>•Phase III, 30 MVA Beta prototype developed and tested (Waukesha and SuperPower)<br>•Full functionality<br>•Progress toward cost goals for major components | •Full size system in "commercial" operating environment<br>•Demonstrate that future economics will be attractive<br>•Acceptable market and technical risk<br>**Projects**<br>•Commercial Project without backup option | •Formal business model<br>•Early movers<br>•Demonstrate value for broader market<br>**Projects**<br>•Customer driven project, without government support | •Market penetration accelerates<br>•Focus on lowering system cost<br>•Increase diversity of product offerings |

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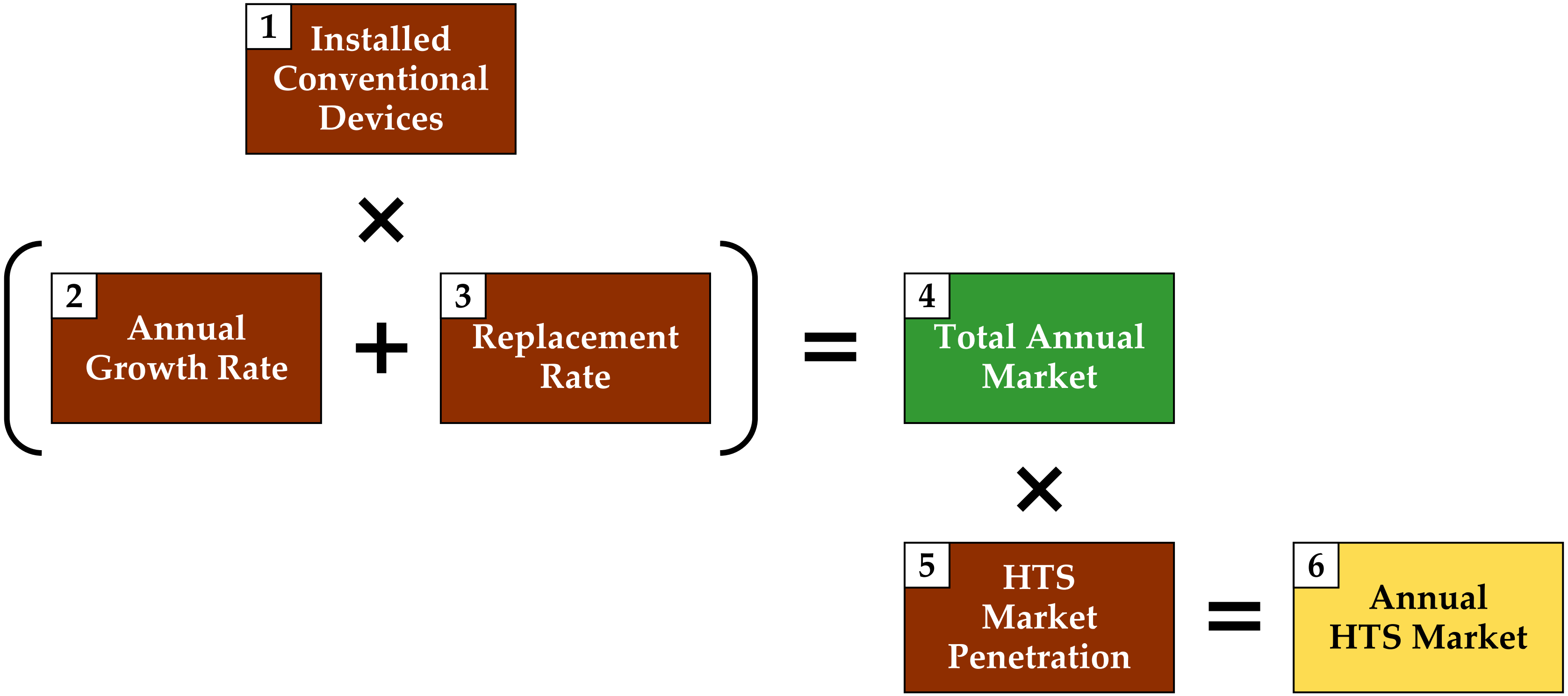
# NCI used a market penetration model to estimate when and how many HTS devices will penetrate their respective markets.



*The objective of this analysis is to estimate the potential size of the HTS market.*

# For each HTS market segment, NCI developed a market penetration model based on industry interviews and a literature review.

| | | |
|---|---|---|
| 1 | **Installed Conventional Devices** | • The size of the market that HTS devices will enter is a key factor for forecasting the size of the HTS market. |
| 2 | **Annual Growth Rate** | • The annual growth rate determines the number of new installations each year. |
| 3 | **Replacement Rate** | • The replacement rate determines the number of new devices that replace existing devices. |
| 4 | **Total Annual Market** | • The annual market is the sum of devices attributed to market growth and the replacement market. |
| 5 | **HTS Market Penetration** | • Certain technology and industry factors are used to estimate when HTS market entry will occur and the rate of HTS technology adoption. |
| 6 | **Annual HTS Market** | • The annual HTS market is the product of the total addressable market and the HTS market penetration rate. |

# The initial size of the market that HTS devices will enter is a key factor for forecasting the size of the HTS market.

1. **Installed Conventional Devices**
2. **Annual Growth Rate**
3. **Replacement Rate**
4. **Total Annual Market**
5. **HTS Market Penetration**
6. **Annual HTS Market**

- The data for the market installed base of devices is obtained from multiple sources.
- In many cases data was available only for the U.S.  In these instance a factor of 3.2 was used to estimate the size of the rest of the world installed base of devices.  This factor is the 2004 ratio of electric generation in the U.S. to the rest of the world.

# The annual growth rate determines the number of new installations each year.

1 Installed Conventional Devices

2 **Annual Growth Rate**

3 Replacement Rate

4 Total Annual Market

5 HTS Market Penetration

6 Annual HTS Market

- In order to determine the total annual market it is necessary to identify the number of devices required to meet the forecasted market growth.
- The incremental market growth between two consecutive years and replacements is the size of the new market.
- The number of devices in the electric power industry is linked to growth in end-use electricity consumption or electric generation capacity.
- The growth rates contained in this report are based on the Energy Information Administration's Annual Energy Outlook 2006 with Projections to 2030, published in February 2006 and the International Energy Outlook 2006, published in June 2006.
  - the Low scenario corresponds to EIA's Low Macroeconomic Growth Case,
  - the Base Case scenario corresponds to EIA's Reference Case, and
  - the High scenario corresponds to EIA's High Macroeconomic Growth Case.

# The replacement rate determines the number of new devices that replace existing devices.

1. Installed Conventional Devices
2. Annual Growth Rate
3. **Replacement Rate**
4. Total Annual Market
5. HTS Market Penetration
6. Annual HTS Market

- The second aspect for determining the total annual market is to identify the number of replacement devices ordered in a given year.
- The replacement rate is assumed to be one half of one divided by the device lifetime.
- However, in some markets the replacement rate is considered to be zero because it was viewed as extremely unlikely that an HTS device would replace the conventional device even after the conventional device failed.

# The annual market is the sum of devices attributed to market growth and the replacement market.

1 Installed Conventional Devices

2 Annual Growth Rate

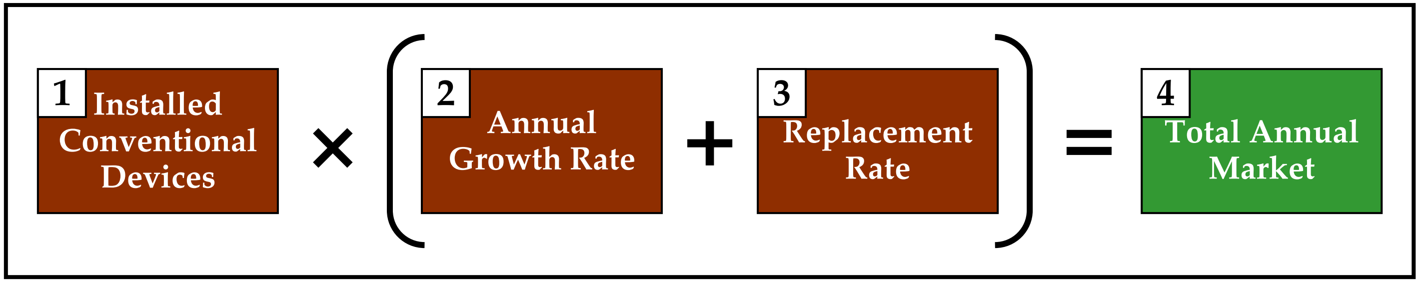
3 Replacement Rate

**4 Total Annual Market**

5 HTS Market Penetration

6 Annual HTS Market

- The size of the annual market is the sum of the new and replacement markets.
  - The new market is determined by multiplying the annual growth rate by the number of installed conventional devices in the prior year
  - The replacement market is determined by multiplying the replacement rate by the number of installed conventional devices in the prior year.



1 Installed Conventional Devices × ( 2 Annual Growth Rate + 3 Replacement Rate ) = 4 Total Annual Market

# Certain technology and industry factors are used to estimate when HTS market entry will occur and the rate of HTS technology adoption.

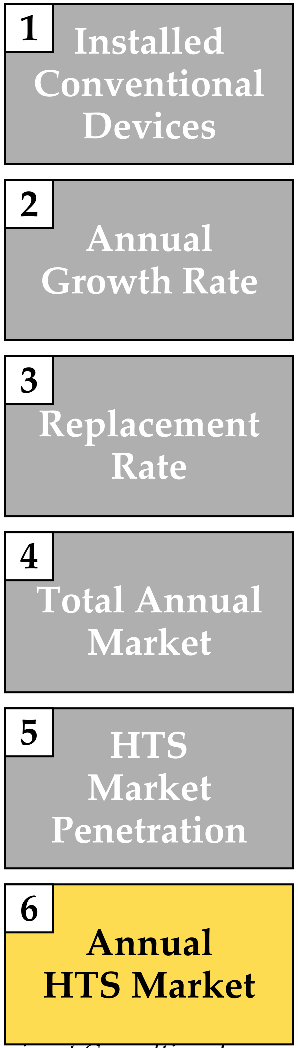
1. Installed Conventional Devices
2. Annual Growth Rate
3. Replacement Rate
4. Total Annual Market
5. **HTS Market Penetration**
6. Annual HTS Market

- The time of market entry of HTS devices depends on the performance of the HTS wire, whether or not HTS wire provides a new capability, and the cost of device components.
- Market penetration depends on the
  - — date of market entry ("Market entry" is defined as the first product that does not require government funding)
  - — how quickly the new technology is adopted, and
  - — the ultimate share of the addressable market.
- To simplify the analysis one market penetration scenario was developed for all market segment in each scenario.
- The NCI market model incorporates the S-shape curve used in the Mulholland Report –

$$F(t) = b\frac{\exp[(t-c)/a]}{\exp[-(t-c)/a] + \exp[(t-c)/a]}$$

- The parameters are as follows:
  - — $t$ is the time measured in years
  - — $b$ is the asymptotic maximum value of HTS market penetration
  - — $c$ is the midpoint in time when half the market is captured (F = $b/2$)
  - — $a$ is the width of the curve, determining how quickly HTS devices capture market share. 76% of the final market share is captured between $t_1 = c - a$ and $t_2 = c + a$. Therefore, $2a$ is the number of years between 12 percent of the final market share and 88 percent.

# The annual HTS market is the product of the total addressable market and the HTS market penetration rate.



- The Annual HTS Market is the product of the addressable market and the HTS market share.
- Once the Annual HTS Market is determined it is possible to project HTS wire requirements for each market segment. In addition, the benefits of HTS devices can be tabulated. The benefits include reducing energy system losses, reducing emissions, amongst others.

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# Key Parameters Market Size

| | | | | Growth Rate for the United States | | | Growth Rate for the Rest of the World | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Est. 2005 US Sales** | **Est. 2005 Rest of the World Sales** | **Replacement Rate** | **Low Scenario** | **Medium Scenario** | **High Scenario** | **Low Scenario** | **Medium Scenario** | **High Scenario** |
| **Power Cable** | 210 miles | 1020 miles | 1.25% of UG | 1.2% | 1.6% | 2.0% | 2.3% | 3.0% | 3.7% |
| **Synchronous Condensers** | 13 – 25 MVA units | 50 – 25 MVA units | 2% | 0.6% | 0.9% | 1.2% | 1.4% | 2.3% | 3.1% |
| **Fault Current Limiter** | 450 units | 1,400 units | 5% | 1.2% | 1.6% | 2.0% | 2.3% | 3.0% | 3.7% |
| **Industrial Motors** | 94 – 5,000 hp units | 1,250 – 5,000 hp units | 0% | 0.2% | 0.8% | 1.4% | 2.3% | 3.0% | 3.7% |
| **Utility Generators** | 28 – 300 MW units | 220 – 300 MW units | 0% | 0.6% | 0.9% | 1.2% | 1.4% | 2.3% | 3.1% |
| **Wind Generator** | 37 – 5 MW units | 110 – 5 MW units | 0% | 6.3% | 6.3% | 6.3% | 5.0% | 6.3% | 8.0% |
| **Medium Transformers** | 1,300 – 30 MVA units | 3,900 – 30 MVA units | Included | 1.2% | 1.6% | 2.0% | 2.3% | 3.0% | 3.7% |
| **Large Transformers** | 120 – 300 MVA units | 360 – 300 MVA units | Included | 1.2% | 1.6% | 2.0% | 2.3% | 3.0% | 3.7% |

# Key Parameters Market Timing and Share

| | Market Entry | | | Years to 10% of Ultimate HTS Market | | | Years to 50% of Ultimate HTS Market | | | Ultimate HTS Market Share (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low Scenario | Medium Scenario | High Scenario | Low Scenario | Medium Scenario | High Scenario | Low Scenario | Medium Scenario | High Scenario | Low Scenario | Medium Scenario | High Scenario |
| **Power Cable** | 2016 | 2014 | 2012 | 5 | 3 | 2 | 15 | 10 | 8 | 25 | 25 | 50 |
| **Synchronous Condensers** | 2014 | 2011 | 2009 | 5 | 3 | 2 | 15 | 10 | 8 | 25 | 50 | 50 |
| **Fault Current Limiter** | 2016 | 2014 | 2012 | 5 | 3 | 2 | 15 | 10 | 8 | 25 | 50 | 50 |
| **Industrial Motors** | 2020 | 2016 | 2014 | 5 | 3 | 2 | 15 | 10 | 8 | 25 | 25 | 50 |
| **Utility Generators** | 2030 | 2020 | 2018 | 5 | 3 | 2 | 15 | 10 | 8 | 10 | 25 | 50 |
| **Wind Generator** | 2014 | 2014 | 2012 | 5 | 3 | 2 | 15 | 10 | 8 | 25 | 50 | 75 |
| **Medium Transformers** | 2018 | 2014 | 2012 | 5 | 3 | 2 | 15 | 10 | 8 | 25 | 25 | 25 |
| **Large Transformers** | 2025 | 2017 | 2015 | 5 | 3 | 2 | 15 | 10 | 8 | 25 | 25 | 50 |

# The market for utility cable appears to be a niche opportunity, focused on alleviating congestion in dense urban areas.

- There are 2 major segments for the HTS cable market
  1. underground transmission cables; and,
  2. conversion of overhead to underground transmission cables*
- There is approximately 5,200 miles of underground transmission cable installed in the U.S. in 2004,[1] and approximately 400,000 miles of overhead transmission cable.[2]
- Recently, undergrounding cable has been given new consideration to reduce the frequency of major power outages and NIMBY concerns.[3] Therefore, we assume that 1% of the overhead cable market will be captured by the underground market.
- Assuming a growth rate of 1.6%[4] and a replacement rate of 1.25% for underground transmission cable.
- However, only one-quarter of this market would require the higher density provided by HTS cables compared to their conventional counterparts.
- Based on the preceding discussion, the first commercial HTS cable can be expected in the 2014 timeframe.
- The rest of the world market is estimated to be 3 times the size of the U.S. market with an annual growth rate of 3.0%,[5] and have a similar timeline for market entry and adoption.

*. Non-HTS transmission cable is defined as greater than 69 kV. HTS "distribution" cables may operate at lower voltages, yet may carry the same power as conventional "transmission" cables.

[1] UDI Platts Directory of Electric Power Producers & Distributors Mailing List 2006 for only the United States and excludes holding companies.

[2] Data for overhead transmission miles of voltage >71 kV obtained from, Edison Electric Institute, Statistical Yearbook of the Electric Utility Industry/2005.

[3] Johnson, Brad. "Out of Sight, Out of Mind: A study on the costs and benefits of underground overhead power lines." Edison Electric Institute. January 2004. Wise, Kristi and Cyril Weiter, "Going Underground: A Growing Reality for Transmission Line Routing." TECHBriefs 2003 No. 3 Burns and McDonnell, 2003.

[4] Energy Information Administration. Annual Energy Outlook with Projections to 2030. February 2006.

[5] Energy Information Administration. International Energy Outlook 2006. June 2006.

# The HTS synchronous condenser is modeled as a substitute for existing FACTS devices.

- An HTS synchronous condenser can be considered an improved FACTS (Flexible Alternating Current Transmission Systems) device.
- There are approximately 40,000 MVAr of FACTS devices installed worldwide as of January 2000.[1]
- The net worldwide installed power generation capacity in 2000 was 3400 GW.[2] Therefore, for every GW of generation capacity there is approximately 12 MVAr of FACTS.
- This ratio is also applicable in the United States. Therefore, in 2004 there was 922 GW of generation capacity,[3] which corresponds to approximately 11,000 MVAr of FACTS.
- The annual growth rate of FACTS devices corresponds to forecasted growth rate for the growth of electric capacity, 0.9% in the U.S.[3] and 2.3% for the world[4]. As a result of the enhancement FACTS provide the power delivery system, a 2% adder is included.
- The HTS synchronous condenser can effectively address 50% of this market.

1. Habur, Klaus and Donal O'Leary, "FACTS – Flexible Alternating Current Transmission Systems For Cost Effective and Reliable Transmission of Electrical Energy, World Bank. http://www.worldbank.org/html/fpd/em/transmission/facts_siemens.pdf.
2. International Energy Agency. World Energy Outlook 2002. 2002. pg 412. http://www.worldenergyoutlook.org/
3. Energy Information Administration. Annual Energy Outlook with Projections to 2030. February 2006. http://www.eia.doe.gov/oiaf/aeo/excel/aeotab_9.xls.
4. International Energy Agency. World Energy Outlook 2004. 2004. pg 192, 432. http://www.worldenergyoutlook.org/

# Today, there are no fault current control products on the market, but utilities have expressed strong interest in the capabilities of such a product.

- The major segments for HTS fault current limiters are the transmission substations that have fault current problems.
- An HTS fault current limiter is a new product that addresses a need not otherwise met.
- The number of transmission level substations in the U.S. is 10,287.[1]
- The percentage of substations upgraded in a particular year is 5% of those with fault current problems.
- One fault current limiter is required per substation with fault current problems.
- When a substation is upgraded either with conventional technology or HTS fault current limiters it will no longer need another upgrade in the time horizon of this analysis.
- The annual growth rate of new transmission substations is equivalent to the average annual growth rate for end-use electricity consumption, 1.6%.[2]
- The rest of the world is assumed to be 3 times the U.S. market with an average annual growth rate of 3.0%.[3]
- The fault current limiter can effectively address 50% of this market.

1. Albert, Réka, István Albert and Gary Nakarado. "Structural Vulnerability of the North American Power Grid." January 2004. http://arxiv.org/PS_cache/cond-mat/pdf/0401/0401084.pdf.
2. Energy Information Administration. Annual Energy Outlook 2006 with Projections to 2030. February 2006.
3. Energy Information Administration. International Energy Outlook 2006. June 2006.

# HTS synchronous motors will compete with large (>1000 hp) high efficiency induction motors in the industrial motor market.

- There are approximately 11,000 industrial motors greater than 1,000 hp in operation in the U.S. in 1996.[1]
- These motors consume 90,307 GWh per year and operate about 7,436 hours per year.[1]
- Because owners of this class of motor generally operate their equipment for a significant fraction of the year, this would an opportunity where improved efficiency can yield sufficient value to justify an HTS solution.
- The U.S. industrial motor market is expected to grow at the rate of growth at the same level as electric consumption in the industrial sector, 0.8%.[2]
- Market entry is estimated to occur in 2016, followed by slowly increasing market share as HTS wire costs decline.
- There is no replacement market for HTS industrial motors as conventional motors will likely be rewound with conventional wire.
- The addressable market by HTS is 25% of the total industrial motor market.
- The rest of the world market is 3 times the U.S. market and grows at an average annual rate of 3.0%.

1. Xenergy. United States Industrial Motor Systems Market Opportunities Assessment. December 1998.
2. Energy Information Administration. Annual Energy Outlook 2006 with Projections to 2030. February 2006.
3. Energy Information Administration. International Energy Outlook 2006. June 2006.

# The market opportunity for HTS generators is likely to be limited to large, base load units.

- In the U.S. the 2003 installed generation capacity was 922 GW; in the rest of the world the 2003 installed generation capacity is (total – U.S.) 2788 GW.[1]
- The U.S. growth rate for total generation capacity is forecasted to be 0.9%, while the rest of the world growth rate for total generation capacity is forecasted to be 2.3%.[1]
- The addressable HTS market is only the new generation capacity that is expected to run as base load units, which are assumed to be 50% of the market. And, of the base load units, 50% would use HTS generators.

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1. Energy Information Administration. International Energy Outlook 2006. June 2006.

# Offshore HTS wind generators may be an opportunity to leverage two key attributes of HTS technology – small and light.

- At the end of 2005, world wide there is 59 GW of installed wind energy capacity of which 9.1 GW is located in the U.S.[1]
- In 2004, there are a total of 10 offshore wind energy projects representing 587 MW of capacity,[2] with 90 MW of new offshore capacity in 2005.[3] In 2010 the forecast is for 4 GW of offshore wind projects out of 24 GW of wind energy installations in world,[3] or approximately 20%. This percentage is applied to the forecasted wind energy installations over the forecast period.
- IEA's World Energy Outlook forecasts wind energy installations to increases at average annual rates of 6.7% from 2005 to 2030.[4] This growth rates apply to the U.S. and world markets, where the U.S. is one-fourth of the world market.
- The addressable HTS market is 50% of all offshore HTS wind farms.

1. World Wind Energy Association (WWEA). http://www.wwindea.org/pdf/press/PR_Statistics2005_070306.pdf.
2. British Wind Energy Association. "Offshore Wind." http://www.bwea.com/offshore/worldwide.html.
3. BTM Consult ApS. International Wind Energy Development World Market Update 2005: Forecast 2006-2010. March 2006
4. International Energy Agency. World Energy Outlook 2004. January 2004. http://www.worldenergyoutlook.org/.

# The market for transformers will not begin to evolve until several working prototypes are successfully field tested for an extended period of time.

- There are 2 major segments for the HTS transformer market
  1. ~30 MVA transformers at distribution substations; and,
  2. >300 MVA transformers at transmission substations and as generator step-up units
- The total U.S. medium power transformer market is approximately 1300 units annually.[1]
- Assuming that the U.S. medium power transformer market size is between 20 and 150 MVA and the large power transformer market is > 150 MVA.
- Based on the relative population of each transformer size in the national inventory,[2] the annual market for large power transformers is 120 units.
- At an average annual growth rate of 1.6%, equal to U.S. end-use electricity consumption.[3]
- However, only one-quarter of this market would require the reduced size and weight and improved reliability provided by HTS transformers compared to their conventional counterparts.
- Based on the preceding discussion, the first commercial ~30 MVA transformer can be expected in the 2014 timeframe with improvements in dielectric technology enabling larger transformers to enter in the market in 2017
- The rest of the world market is 3 times the U.S. market and grows at an average annual rate of 3.0%.[4]

1. Golner, Tom. "Transformer Conductor Requirements" 2006 Wire Development Workshop. http://www.energetics.com/meetings/wire06/pdfs/session2/golner.pdf
2. Mulholland, Joseph, Thomas Sheahen and Ben McConnell. Analysis of Future Prices and Markets for High Temperature Superconductors. June 2003. pg 8-3.
3. Energy Information Administration. Annual Energy Outlook with Projections to 2030. February 2006.
4. Energy Information Administration. International Energy Outlook 2006. June 2006.

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