Leveraging Transformer Manufacturing and Operational Insights to Drive the Development of Next-Generation Substation Technology

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ARPA-E
Roundtable - Active Substations with Flexible Large Power Transformers
Alexandria, VA
September 25-26, 2025

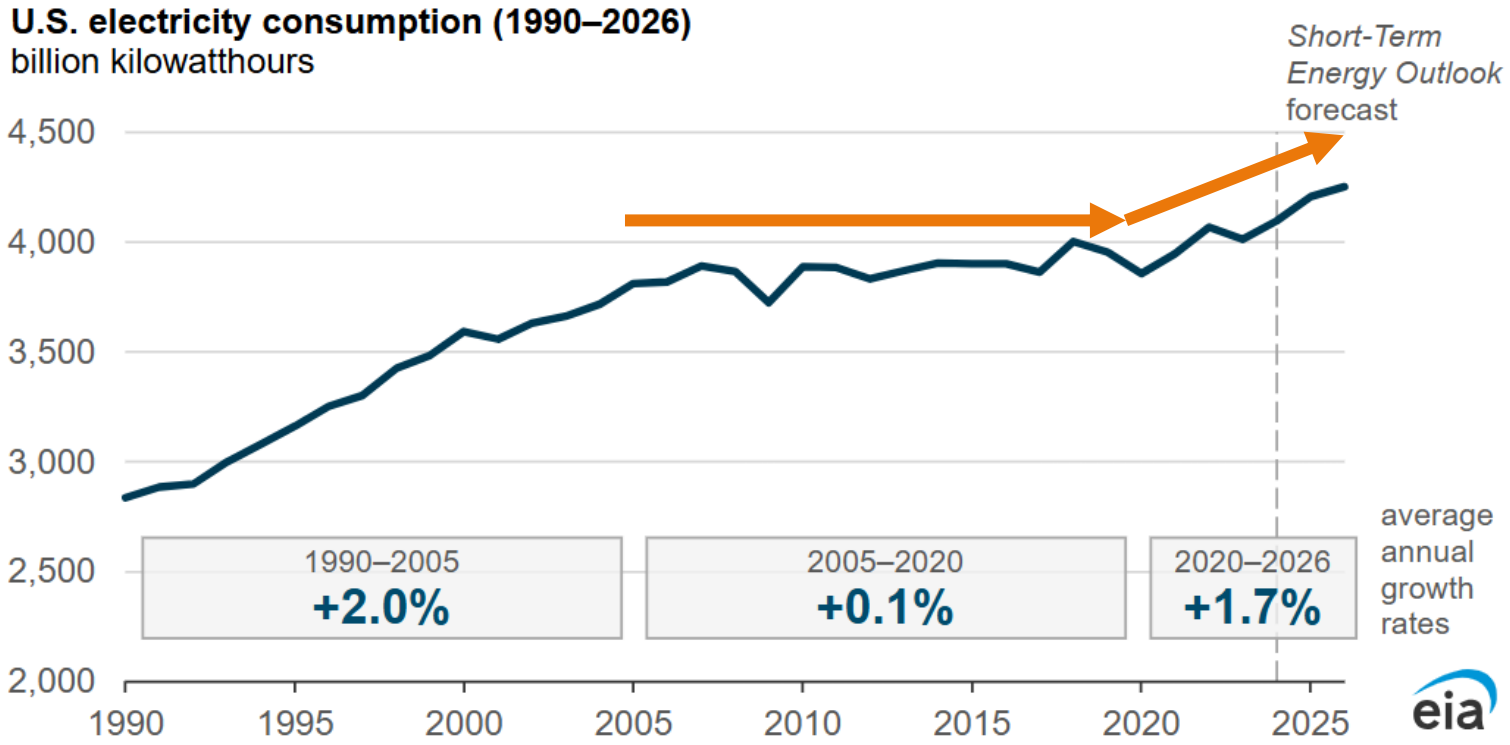


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Electricity Consumption - Trends [acc. to eia]

After more than a decade of little change, U.S. electricity consumption is rising again

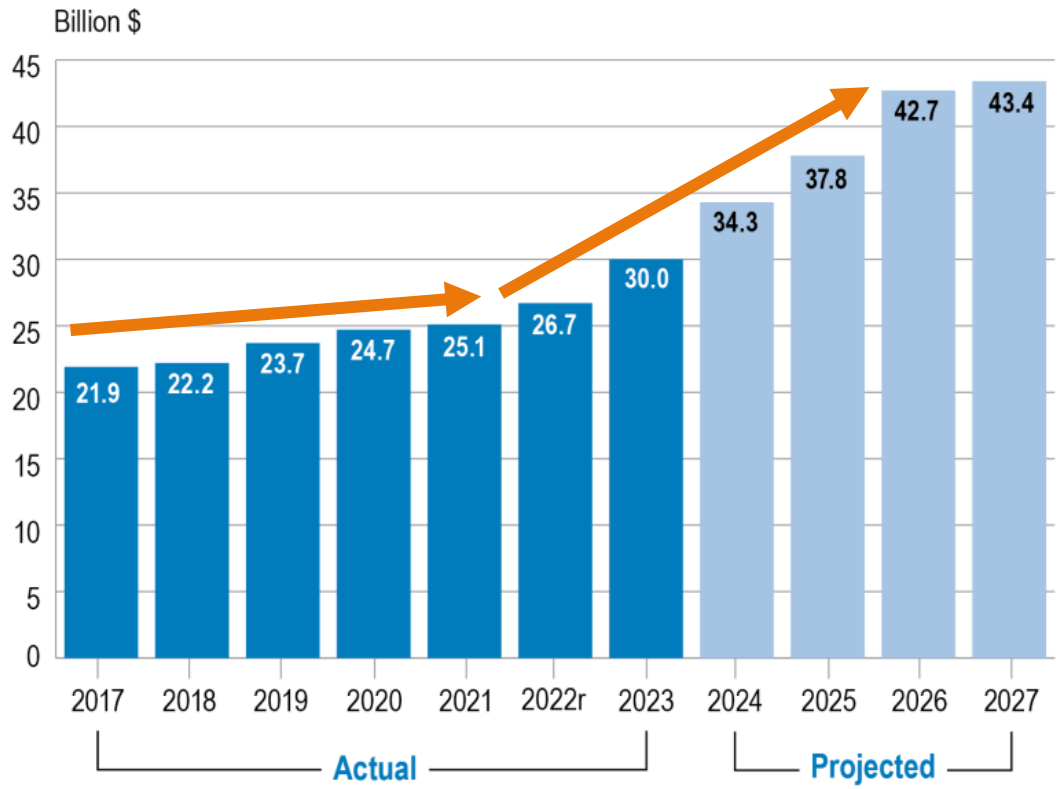


Data source: U.S. Energy Information Administration, *Monthly Energy Review* and *Short-Term Energy Outlook*, May 2025
Data values: Electricity Overview (history) and U.S. Electricity Industry Overview (forecast)

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Transmission Investment of IOUs [acc. to EEI]

Actual and Projected Transmission Investment (Nominal Dollars)



Investment of investor-owned electric companies and stand-alone transmission companies. Actual Investment figures were obtained from the EEI Property & Plant Capital Investment Survey supplemented with FERC Form 1 data. Projected investment figures were obtained from the EEI Transmission Capital Investment Forecast Survey supplemented with data obtained from company 10-k reports and investor presentations.

r = revised

Source: Edison Electric Institute Business Analytics Group.

Updated January 2025.

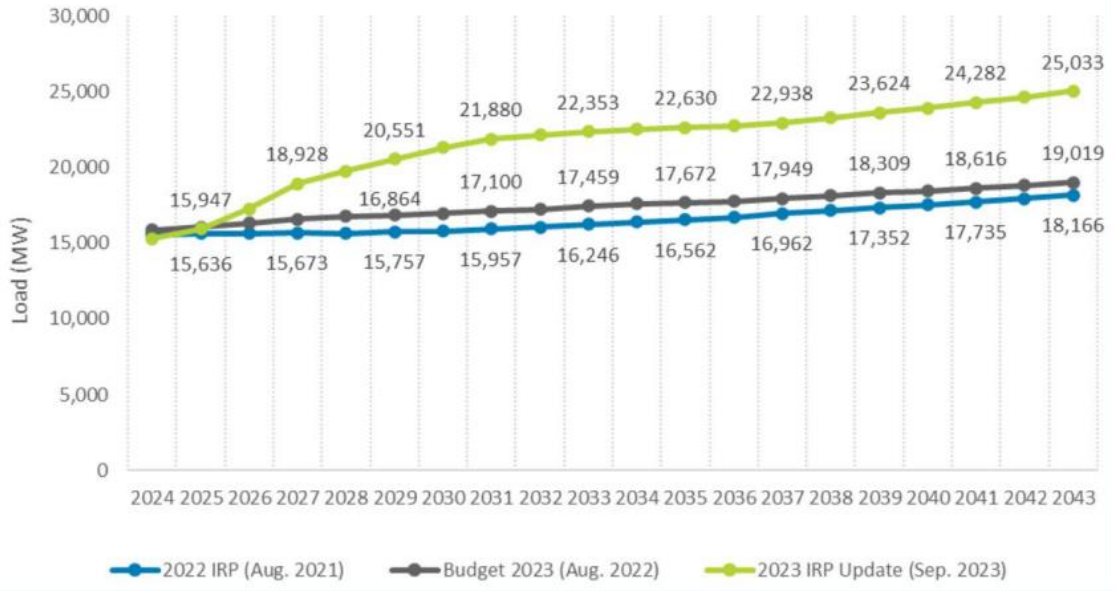
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Long term Forecasting: examples of revisions year-over-year

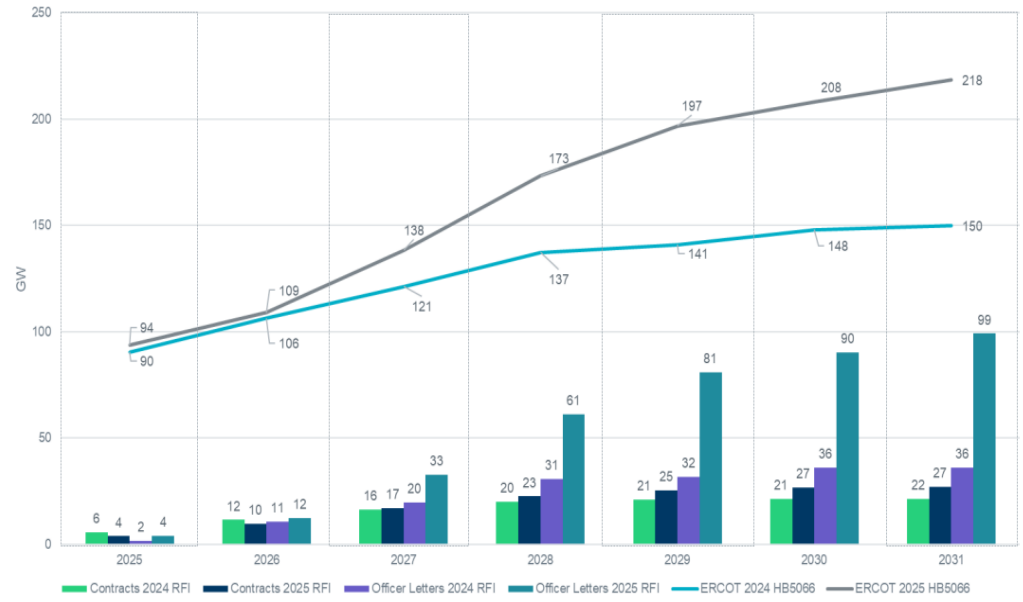
2023 IRP Update load forecast for the 20-year period spanning the winter of 2023/2024 through the winter of 2042/2043.[20]

Figure 3: Georgia Power Projected Winter Peak Demand



SOURCES | Georgia Power Company, *2023 Integrated Resource Plan Update* (February 24, 2023), pp. 6-10, and the *Load and Energy Forecast* Technical Appendix.

TSP-Provided Load Forecast Comparison of Demand (2024 to 2025)



Key Takeaway: The 2025 TSP-Provided Load Forecast is substantially higher than what was submitted in 2024.

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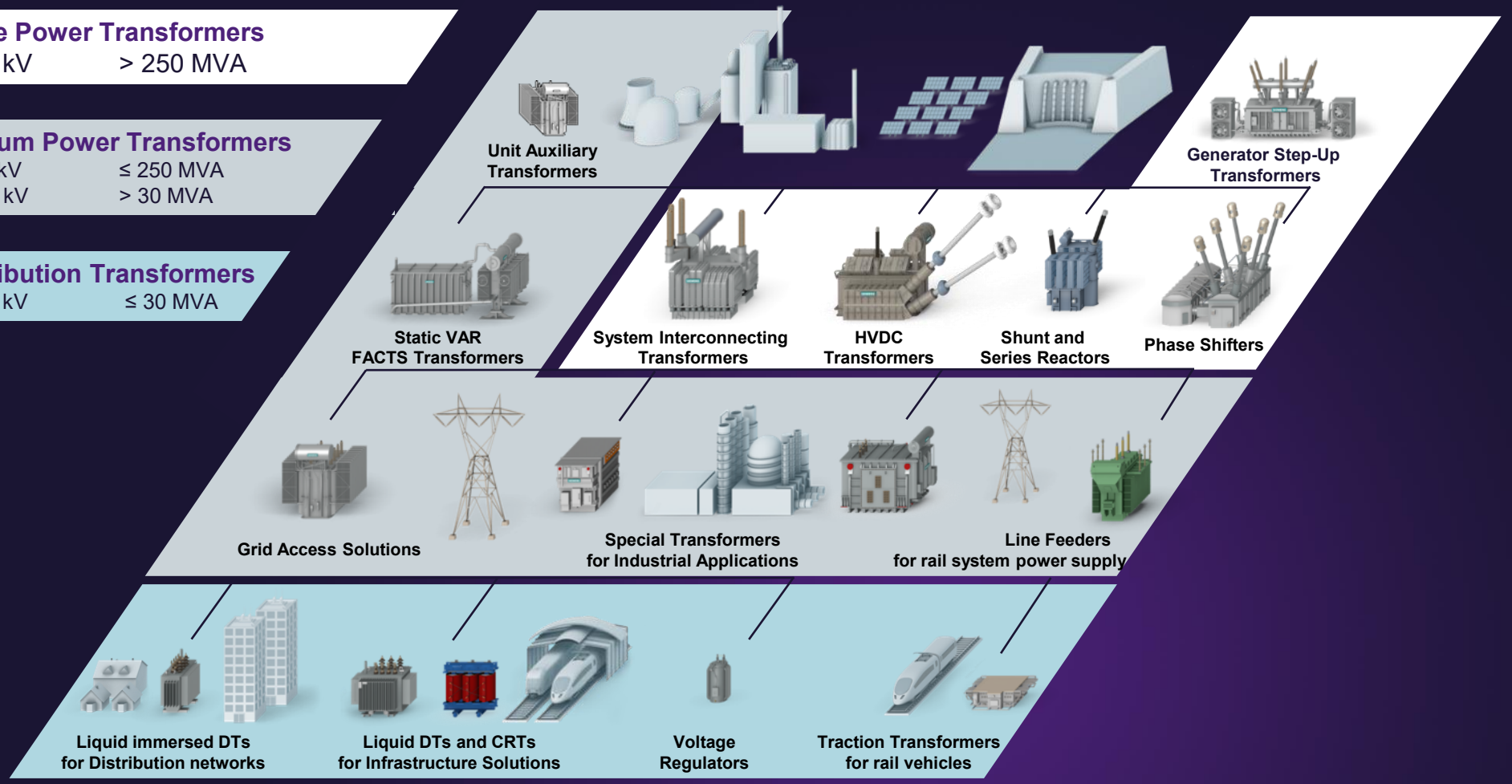
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Transformer types

Large Power Transformers
>300 kV > 250 MVA

Medium Power Transformers
≤ 300 kV ≤ 250 MVA
> 72,5 kV > 30 MVA

Distribution Transformers
≤ 72,5 kV ≤ 30 MVA



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Power Transformers and considerations for Next-Generation Substation Technology

- Power transformers are custom-made. Every user has it's own technical specification.
  - Optimized / tuned to the grid conditions where they will be operating.
  - Electric grid: Power [MVA], voltage, tap voltage, impedance voltage, dielectric insulating levels, short circuit power.

  - IEEE Std C57.12.00 (Standard for Gen. Requirements for Liquid Immersed Transformers) defines usual service conditions:
    - Temperature, altitude.
    - Supply voltage characteristics.
    - Load current (incl. harmonics).
    - Frequency above or below rated value (60 Hz).
    - Maximum continuous operating voltage.
    - Step-up, step-down, system-tie, other.
    - Loading other-than-rated (short time with normal life expectancy or other loading that results in reduced life expectancy) IEEE Std C57.91.
  - IEEE Std C57.12.00 defines unusual service conditions: Temperature, altitude, vapors, dust, explosive mixtures, others.
  - Testing: Routine, Design and Other test. IEEE Std C57.12.00
    - Performance: resistance, ratio, polarity, no load and load losses, impedance voltage, zero sequence impedance, temperature rise with DGA, sound level, short-circuit capability (3-ϕ, 1-ϕ, L-L, L-N… often w. infinite bus assumption).
    - Dielectric: applied AC, induced AC with PD measurement, BIL FW/CW, BSL.
    - Mechanical.

    Existing technology is very reliable !

    ➔ How to assess reliability of new technologies?

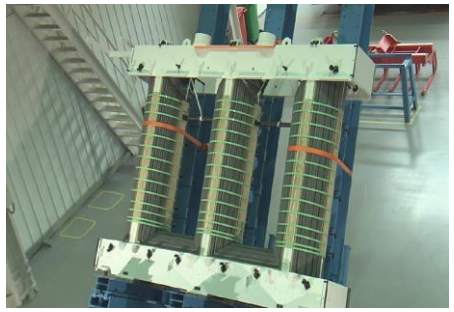
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Transformer Manufacturing: step by step



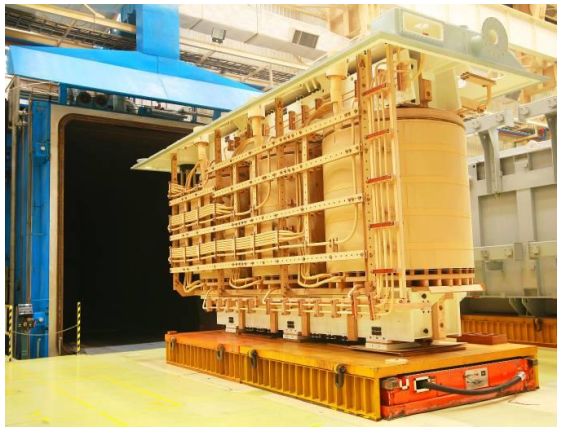


Winding manufacturing





Core cutting & stacking



Active part (core & coils) drying and pressing



Final assembly & oil filling

Ref dimensions:
(450 MVA 230 kV)
H: ~ 8 m
L: ~ 11 m
W: ~ 9 m
H: ~ 8 m
Mass: ~ 270 t



Final testing (FAT)

Keep in mind: Manufacturing is only one of the several steps along the process.
1a. Customer RFQ ➔ 1b. Tendering (pre-design for offer and costing) ➔ 1c. Contract award ➔
➔2a. Design (design review) ➔ 2b. Procurement of materials ➔ 2c. **Manufacturing** ➔ 2d. Testing ➔
➔ 3a. Disassembly ➔ 3b. Shipping ➔ 3c. On-site assembly ➔ 3d. Testing ➔ 4d. Energization ➔ Service

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Power Transformers and considerations for Next-Generation Substation Technology

- Impact and interaction with the real grid (not only in a laboratory environment). Grid resiliency.
- Usual, unusual and emergency operating conditions.
- Black start conditions.
- Protection & control systems.
- Does the new technology have an inherent impedance?
- Impact on other grid equipment without the impedance and associated current limiting (and transient “damping” effect) effect produced by traditional transformers?
- Maintenance & servicing during lifetime.

Analysis of AC transformer reliability

cigre TECHNICAL BROCHURES
September 2024 - Reference 939

Failure rate (world): 0,3% (substation transformers)

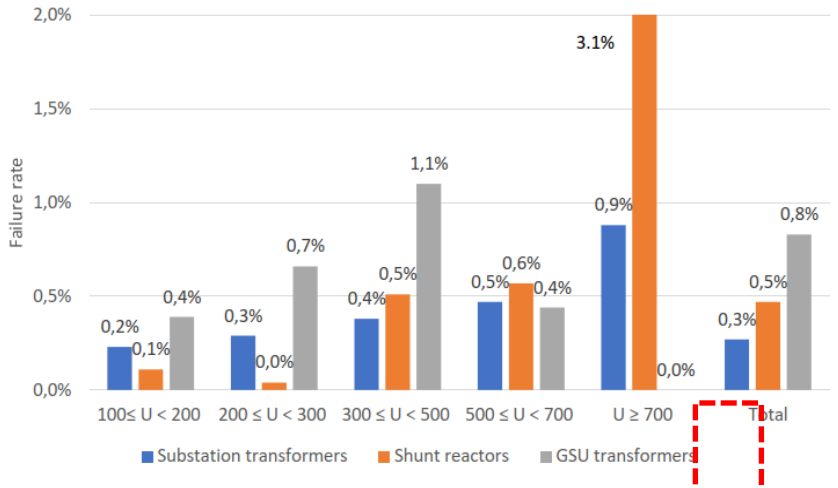


Figure 22: Failure rate dependent upon voltage class and application.

Age profile (world)

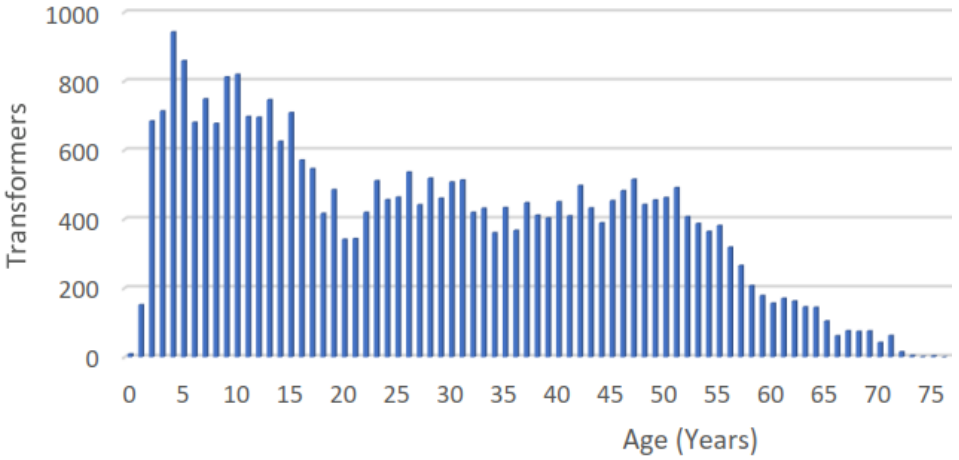


Figure 17: Age profile for in-service transformers.

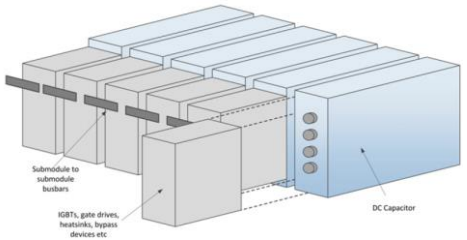
- Expected failure rate and life expectancy of the new technology? ➔ **Reliability is key when evaluating any new technology!**

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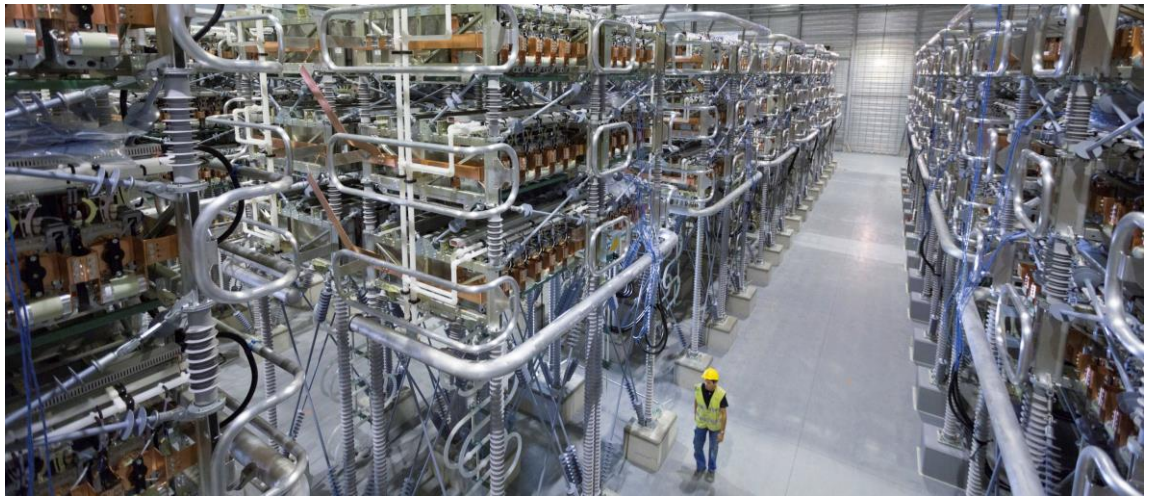
We have experience with power electronics based equipment in the power systems: SVC and VSC-HVDC

Manufacturing

	Transformer	Converter
Manufacturing	- Labor intensive - Skilled labor force - Special factories and laboratories for high voltage testing	- Highly automated - Labor force can be quickly trained - Modular factory set-up and small laboratories for voltage and power tests
Transportation Unit	270 t	< 2 t



CIGRE Green Book HVDC



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Reliability

	Transformer	Converter
Failure Rate	- Failure rate 0.3 %	- FEU: 0.5 % - SEU: 1 % - FOR: 2
Maintenance	- Maintenance on the unit under operation	- Shutdown every 1 – 3 years for app. 1 week
Failure cause		- C&P - Auxiliary systems
Life time	- > 40 years	- Design Life time 30 – 35 years - Mid-life refurbishment of the C&P system is required

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Operation

	Converter
Short circuit capability	- Overcurrent limitation by the converter to app. < 1.3 p.u. • Reduction of short circuit currents • New protection principles are required
Transient voltage stresses	- Converters are designed for high LI and SI voltage stress
Voltage control capability	- High dynamic in voltage control
Inherent impedance	- Inherent impedance is required for network stability - Converters in the Power Systems do not have an inherent impedance, in certain frequency ranges the converter relies on the transformer damping to provide impedance and network stability

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