Trends in volumetric-energy efficiency of implantable neurostimulators: a review from a circuits and systems perspective

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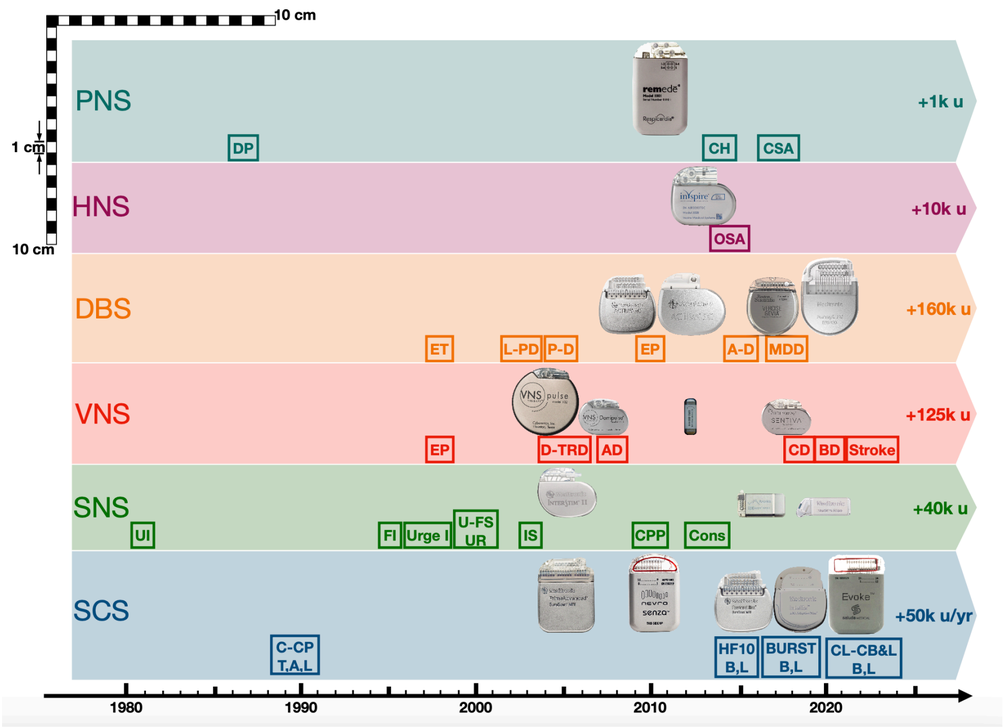
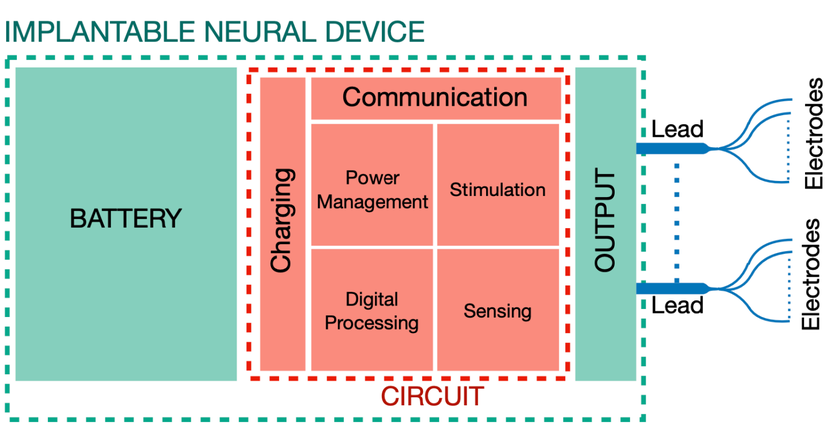
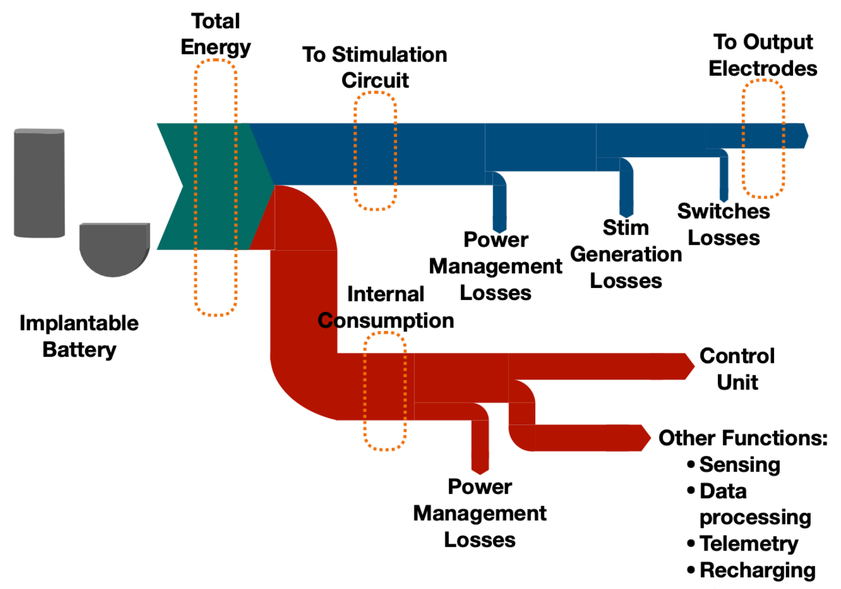
Abstract

- Review of state-of-the-art commercially available neurostimulators, analyzing key design parameters and performance metrics.
- Analysis covers 45 implantable medical devices targeting six neural areas: deep brain, vagus nerve, spinal cord, phrenic nerve, sacral nerve, and hypoglossal nerve.
- Identification of design trends and opportunities for innovation within the neurostimulator industry including device miniaturization, battery technology advancements, and power consumption patterns.

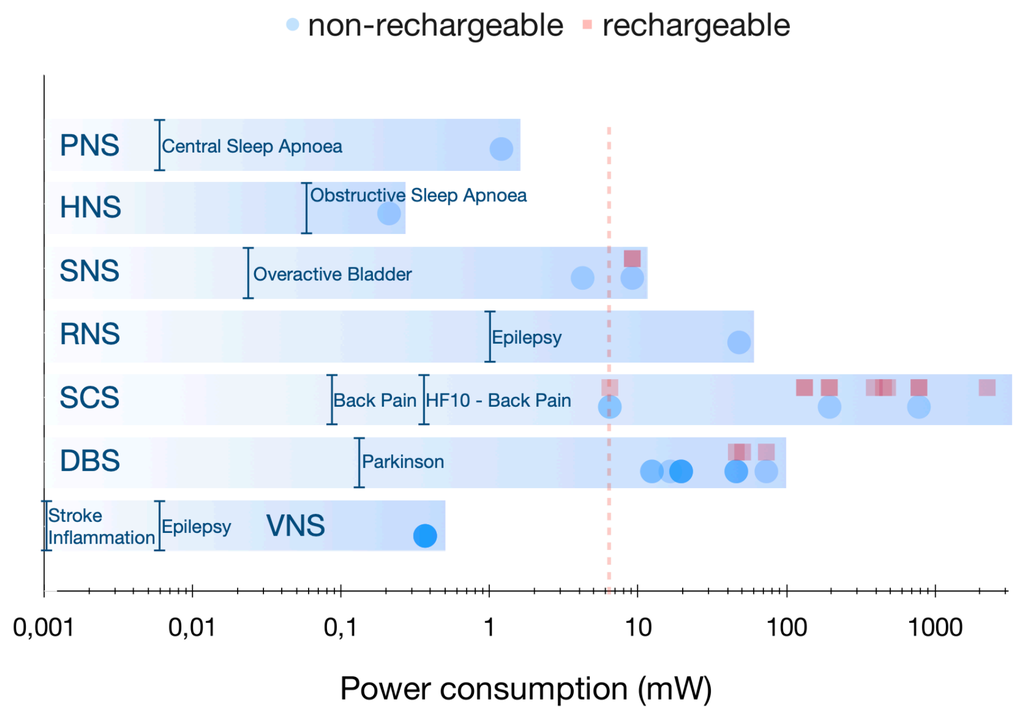


Generic Device Architecture and Power Distribution





Consumption of Different Therapies



Normalized Device Volume vs. Approval Year

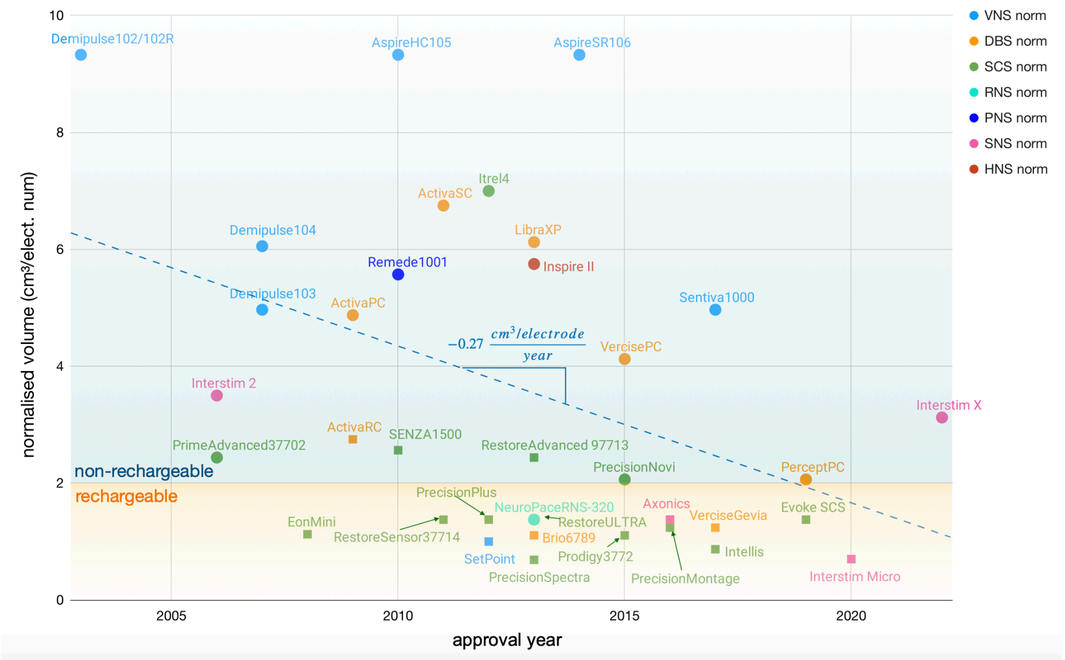
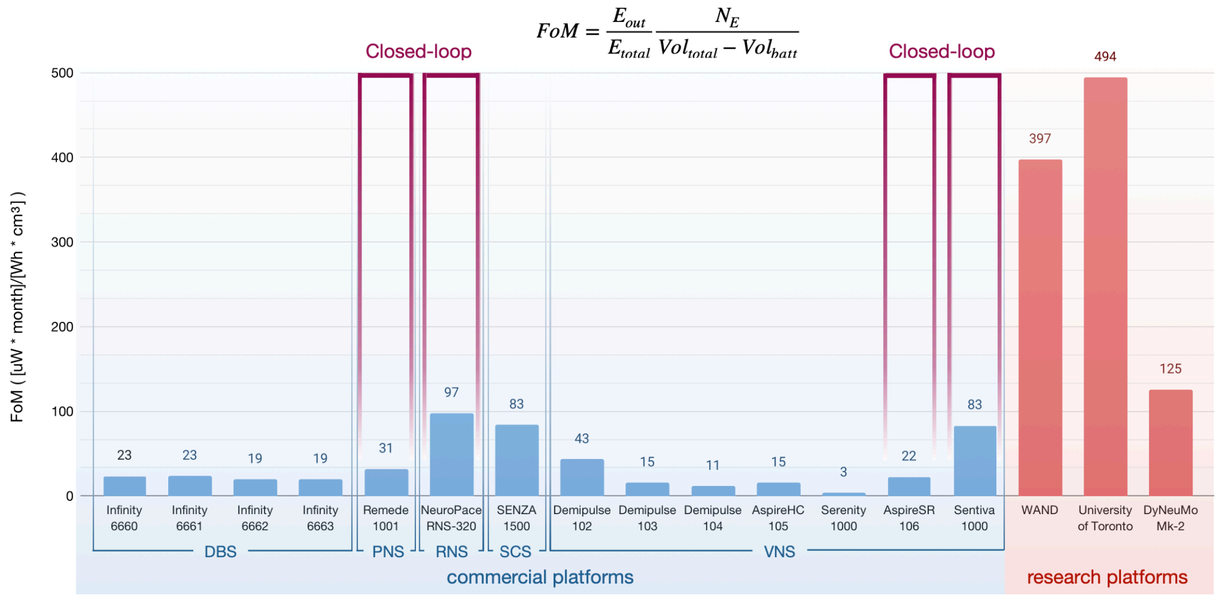


Figure of Merit

$$FoM = \frac{E_{out}}{E_{total}} \frac{N_E}{Vol_{total} - Vol_{batt}}$$



Conclusions

- **Design Trends**: Analysis of 45 devices revealed a trend of neurostimulator volume reduction at a rate of 0.27 cm³/electrode per year, with the smallest form factors found in rechargeable platforms.
- **Battery Technology Limitations**: Despite volume reduction benefits, current rechargeable battery technologies have lower volumetric energy densities compared to non-rechargeables, impacting battery capacity and necessitating frequent recharges.
- **Energy Efficiency**: A large portion of the energy budget is consumed by internal activities rather than being delivered to the tissue, indicating significant potential for improvement in low power circuit design.
- **Figure of Merit (FoM)**: Introduction of a FoM to compare neurostimulators, highlighting a clear performance gap between commercial devices and advanced research platforms due to better volume/electrode trade-offs in the latter.

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