

Power semiconductors for an energy-wise society

- A brief review of IEC whitepaper

Gourab Majumdar, PhD, Fellow IEEE,
Senior Fellow, Mitsubishi Electric Corporation, Japan

- Background: IEC Whitepaper project
- Highlights of each section of IEC Whitepaper
- Conclusion: Recommendations from IEC Whitepaper



White paper

Power semiconductors
for an energy-wise
society

IEC White Paper Project

A collection of practical insights into the market-oriented, market-driven, and market-oriented roles that power semiconductors play in a wide range of industries and society as a whole

- With power modules in mind, and with an emphasis on applications that handle relatively large amounts of power,
- In addition to Si, WBG is also mentioned

Three features of this white paper

(Published in October 2023)



Our company led the project

As a major manufacturer of power semiconductors, we proposed a theme at the IEC-MSB (Market Strategy Board) in October 2022 and led the project until the publication of the white paper.

Bringing together "global all-stars" in the power semiconductor field

Together with experts from around the world, the project team discussed power semiconductor technology, markets, international standards, certification systems, regulations, etc.

Recommendations to stakeholders

Summary of power semiconductor applications, sectors and technological trends, highlighting the need for the development, coordination and expansion of respective international standards and certification systems

Examples of members who participated in the IEC white paper

The people who contributed to the development of the IEC White Paper were from 10 countries, 25 from industry, 29 from universities, and 7 from government and other consultants.



Management team



- Background: IEC Whitepaper project
- Highlights of each section of IEC Whitepaper
- Conclusion: Recommendations from IEC Whitepaper



White paper

Power semiconductors
for an energy-wise
society

| The structure of the white paper

The white paper is composed of 5 sections

Section 1 introduces **the concept** of an energy-wise society, **the role** and operating principles of power semiconductors, and **the impact** of such devices on the UN Sustainable Development Goals and on the IEC Strategic Plan.

Section 2 presents the most **important power electronic applications** relevant to an energy-wise society and considers **the forces** that are driving the current and future development of power semiconductors.

Section 3 reviews **major developments affecting power semiconductor devices** as key components in power electronic applications, from different perspectives. These developments are discussed in relation to the **industry value chain** (chip and module). **Sustainability and life cycle assessment** topics leading to a circular economy are also included for the first time in such a white paper.

Section 4 considers **state-of-the-art standards** as well as **new standards requirements** that are arising in response to **new challenges** introduced by the development and emerging applications of power semiconductors.

Section 5 provides **conclusions and some key recommendations**. It considers what the changes discussed in the previous sections mean for **the IEC, its stakeholders and future standards works**.

Towards an energy-wise society --- Foreword [1/1]

Power semiconductors provide economic, environmental, and social value as key electronic components that support an electrified society and contribute to achieving the United Nations Sustainable Development Goals (SDGs).

SUSTAINABLE DEVELOPMENT GOALS

7 AFFORDABLE AND CLEAN ENERGY



《Goal 7: Energy for everyone and in clean form》

Ensuring the high energy efficiency required to convert renewable energy sources (solar, wind, hydropower) into electrical energy and supply renewable energy to consumers

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE



《Goal 9: Create a foundation for industry and technological innovation》

Clean and green technologies to foster innovation and build sustainable industries and infrastructure (improving factory efficiency using motor drives and robotics)

8 DECENT WORK AND ECONOMIC GROWTH



《Goal 8: Decent work and economic growth》

Realization of new industries and businesses using power semiconductors (green hydrogen, high-speed charging network for electric vehicles (EV), etc.)

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

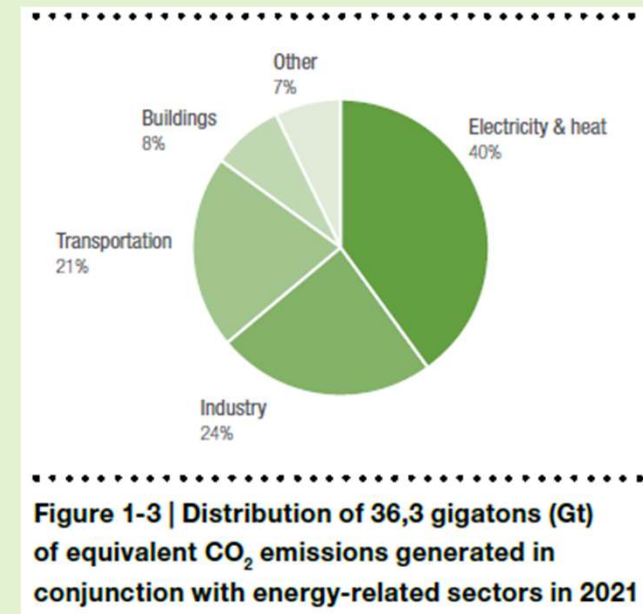
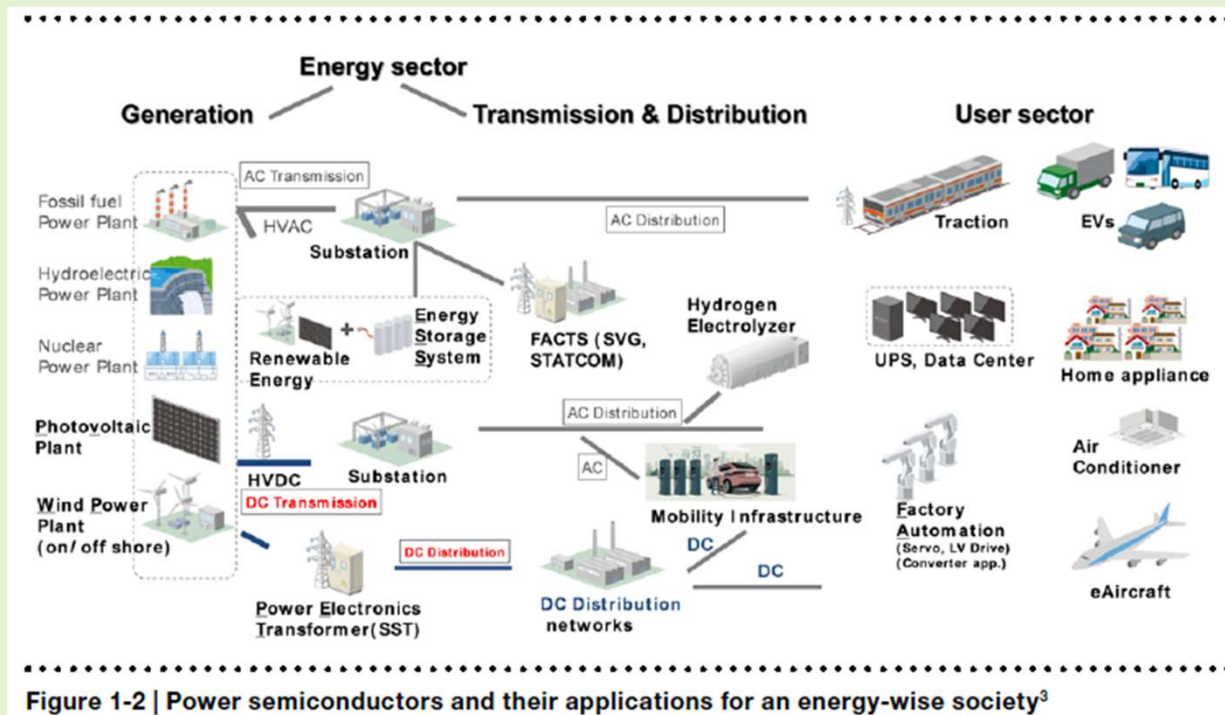


《Goal 12: Responsibility for production, responsibility for consumption》

Renewable energy, electric vehicles and green hydrogen can reduce dependence on fossil fuels in transportation and various industrial processes

Towards an energy-wise society --- Foreword [2/2]

Examples of energy-wise society-related applications of power semiconductors are in bold in Fig. 1-2. In the Energy sector, "power generation using fossil fuels → renewable energy" is required, and in the user sector, "fossil fuel → electrification" is required.

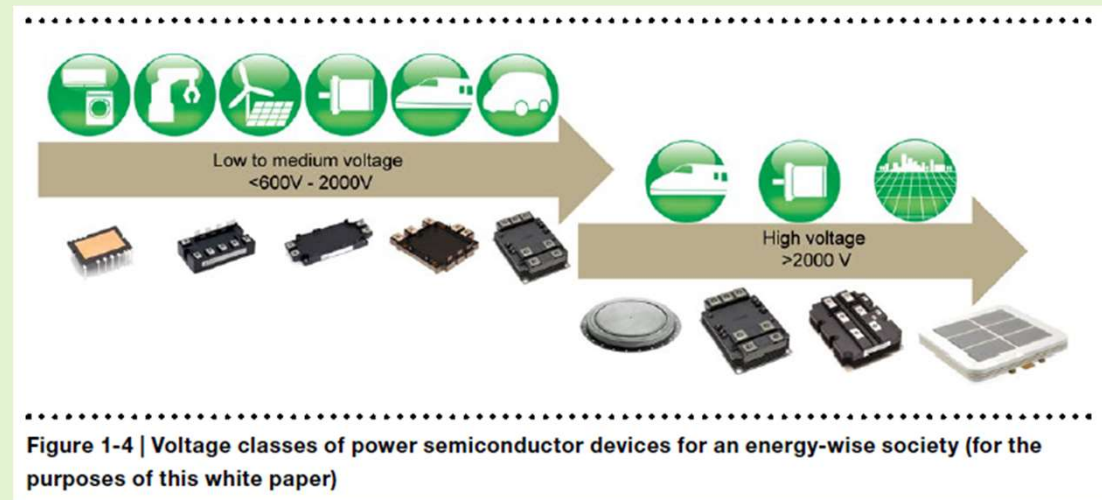


Power needs will rise in line with trends in both sectors, and efficiency improvements will become more important.

Purpose and scope of the IEC White Paper

Using a market-oriented, driven, focused approach, we clarify how power semiconductors are used, explain their importance (future, WBG, supply chain, standardization), and make recommendations.

- How power semiconductors contribute to energy-wise applications
- Positioning of WBG in each application
- Conventional, current, and future power semiconductors
- Focus on relatively high power over 600V, technology trends, supply chain, etc.
- Related standardization, future standardization, and cooperation between the semiconductor industry and applications



Background of the IEC White Paper

Recommends the need for power semiconductors, which will play a central role in an “energy-wise society,” and their international standards.

“energy-wise”3 keywords

Key device
for “energy-wise”

Key components to reduce power consumption and efficiently convert electrical energy

Diverse applications
for “energy-wise”

New materials such as SiC, GaN are being applied to advanced power semiconductors in applications, and implementation in many fields is rapidly progressing.

The need to develop international standards
for “energy-wise”

However, international standards and certification systems are insufficiently developed. The number of products that do not comply with international standards will increase, and cooperation among manufacturers, users, and regulators will be hindered, which may impede the healthy growth of the global power semiconductor market.

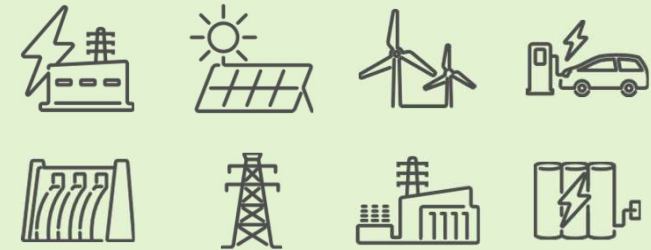
Power electronics trends and future perspectives

Power semiconductors will play a major role in realizing an "energy-wise society" through various power electronics applications.

Power Electronics

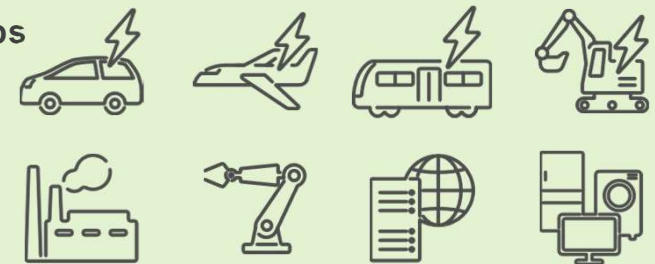
1. Power Generation, Transmission and Distribution (Energy Sector)

- Power transmission and distribution grid: Flexible AC transmission system (FACTS) and high voltage DC transmission (HVDC)
- Renewable energy: Solar power generation, Wind power generation
- Other: Green hydrogen generation, Semiconductor-based solid-state transformers and circuit breakers, Energy storage systems, EV chargers and other mobility infrastructure



2. Electrification (User sector)

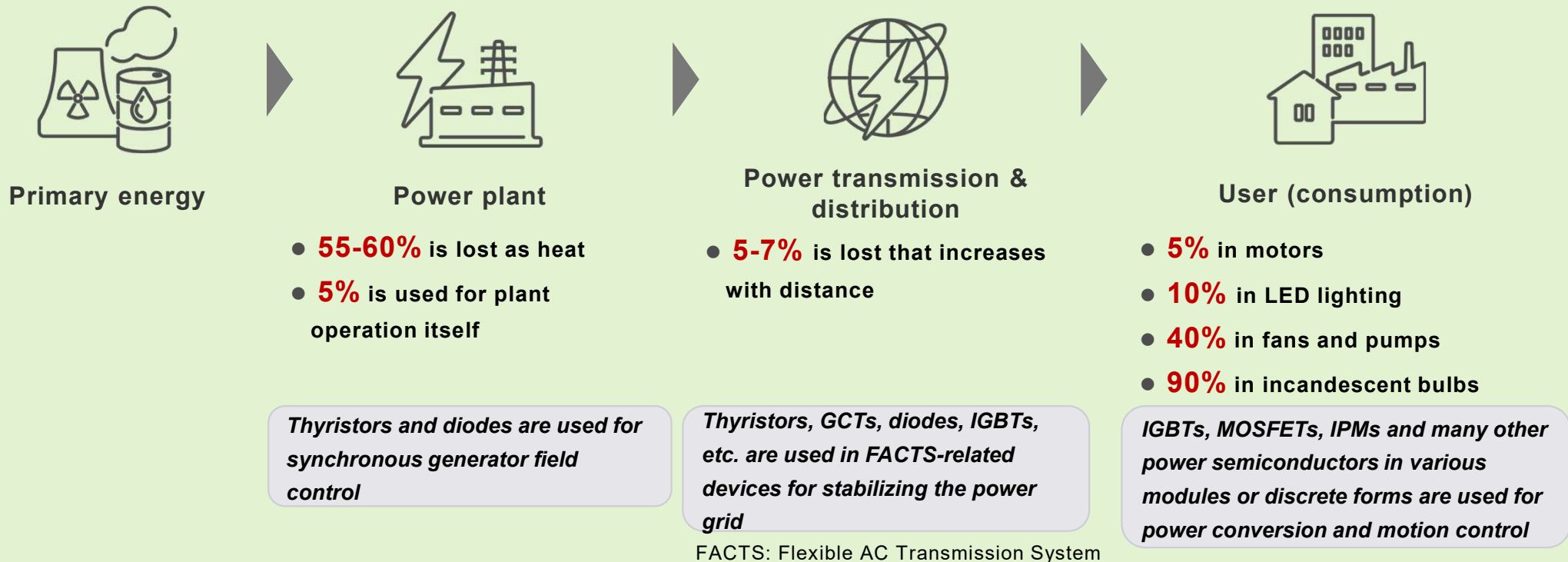
- Electric mobility: Electric cars, Electric railways, Electric aircraft, Electric ships
- Automation of production processes (FA), Industrial motors and Inverters
- Various heavy industry equipment and high-power converters
- Welding equipment and medical equipment
- Air conditioning equipment such as heating and cooling, home appliances
- Data centers and communication IT equipment



2.1 Electricity Sector: Conventional Power Generation, Transmission and Distribution Systems

In conventional power systems, two-thirds of primary energy is lost, and environmental problems arise from mining and burning.

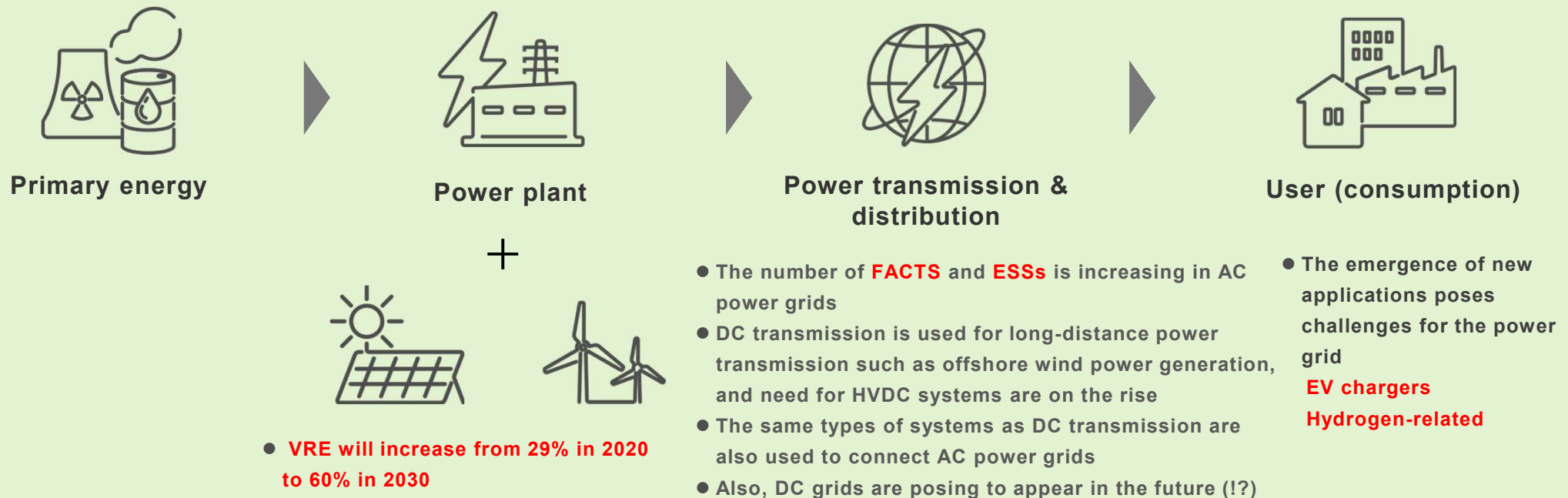
In conventional power systems, power semiconductors play an important role but are hidden by the mechanisms and are not noticeable.



2.1 Electric power sector: growing usage of power semiconductors

- In the future, renewable energy will increase, and power generation will move from centralized to decentralized.
- DC power transmission will be used for long distances, and new applications will expand.

Increasing scope of applications for power electronics (power conditioners, FACTS, ESS, HVDC)



VRE: Variable Renewable Energy FACTS: Flexible AC Transmission System ESS: Energy Storage System HVDC: High Voltage DC

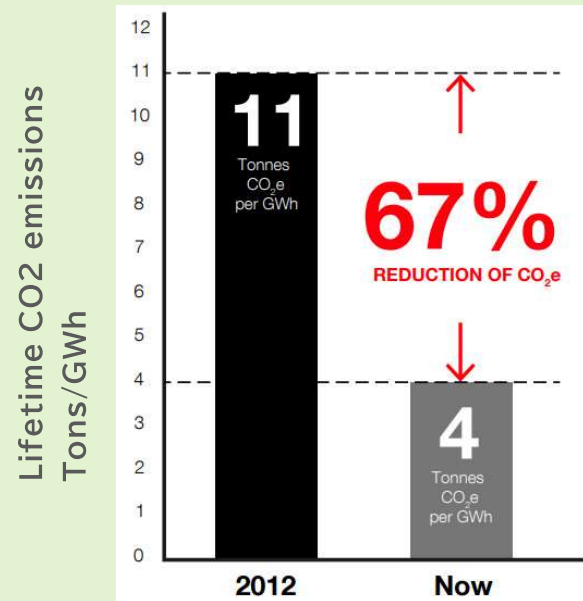
2.1 Power sector: Importance of DC power grid (HVDC) and power semiconductor performance

The HVDC market is growing at a CAGR of 11%. Cumulative 200GW by 2020, reaching 50GW/year by 2030.

LCA comparison example of HVDC system contributing to energy-wise
--- improving the performance of power semiconductors is important

- **LCC-HVDC: Thyristor-based**
suitable for large power generation
Hydroelectric power generation in
remote areas ~ Large cities 800kV,
1100kV ~ 12GW
- **VSC-HVDC: Capable of black**
starting without requiring a directly
connected synchronous generator.
- **VSC is expected to increase in the**
future. Uses IGBTs. Used in
offshore wind power generation, etc.
320kV ~ 4GW

LCC: Line-commuted Current source Converter
VSC: Voltage Source Converter



- CO2 emitted during the service life is a KPI for manufacturers of HVDC systems.
- This figure shows a comparison of two different generations of HVDC equipment. A large part of this difference is caused by the evolution of IGBT.
- It has a long operating life of more than 20 years and has a redundancy concept that prevents power semiconductor failures from causing the entire system to stop.

2.2.2 Vehicle electrification

According to IEA NZE, the proportion of EVs in new car sales needs to increase from 16% in 2022 to 67% in 2030.

Low loss in power semiconductors makes xEVs with low environmental impact and high efficiency possible

1. CO2 generation in EV (LCA)

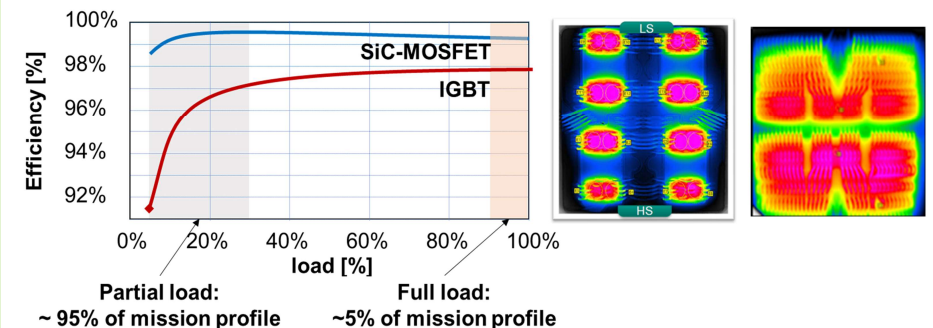
- If VRE is used for driving, most of the CO2 will be generated during EV manufacturing
- It is estimated that 40% of this will be related to battery manufacturing.
- Electronic parts will account for less than a few percent.

2. xEV (BEV, HEV, FCV)

- Power semiconductors are used in the circuit shown in the upper right diagram.
- The total cost of power semiconductors is currently \$330, which is an order of magnitude more than that of internal combustion engine vehicles. It will increase further for high-power vehicles and will continue to increase in the future **with trend to apply complex systems having higher WBG content.**
- Efficiency of power semiconductors affects "cruising distance"
 - SiC low loss** → improves efficiency and power density, which are important for EVs
 - SiC high-temperature operation** → leads to air cooling of OBC and BMS
 - SiC high-speed operation** → improves control stability and improves filter performance, weight reduction
 - Most EV mission profiles are less than 30% of the rating, making SiC advantageous**
 - As a result, the cruising distance can be increased by around 5% or battery consumption can be reduced by switching to SiC.
 - 79% of the SiC requirement in 2027 is expected to be xEV



On Board Charger
Battery Management System
High-to-low voltage DC/DC
Traction converters



Semiconductor loss comparison between Si-IGBT and SiC (IEC white paper Fig.2-4)

3 Trends and futuristic outlook for power semiconductor devices

Power semiconductors are broadly divided into chip and module technologies, which continue to advance by mutually stimulating material technology.

Power Semiconductor Devices

1. Power Semiconductor Chip technology

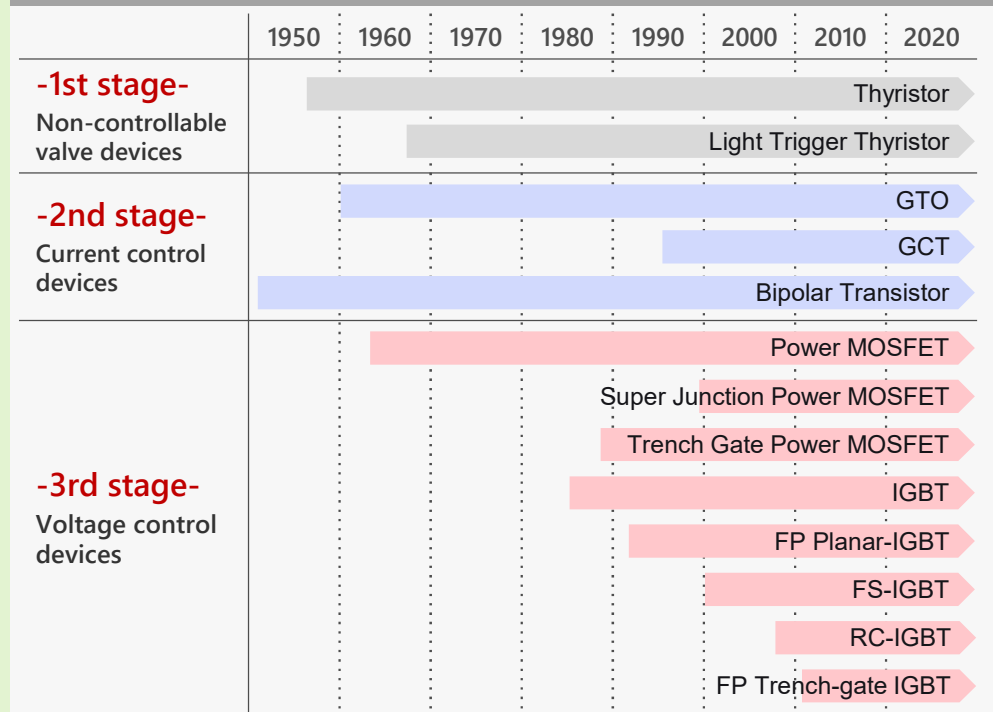
- Silicon power semiconductor technology, its history and future trends
- Thyristors, GCTs, GTOs, IGBTs, and diodes
- WBG chip technology, its history and future trends
- SiC semiconductor chip technology, GaN semiconductor chip technology
- Future WBG materials ---UWBG---- Ga₂O₃, AlN, etc.

2. Power Module Technology

- Industrial module with general purpose shape
- IPM* and application-specific modules
- WBG power module

*IPM: Intelligent Power Module

Silicon Power Chip Technologies, history

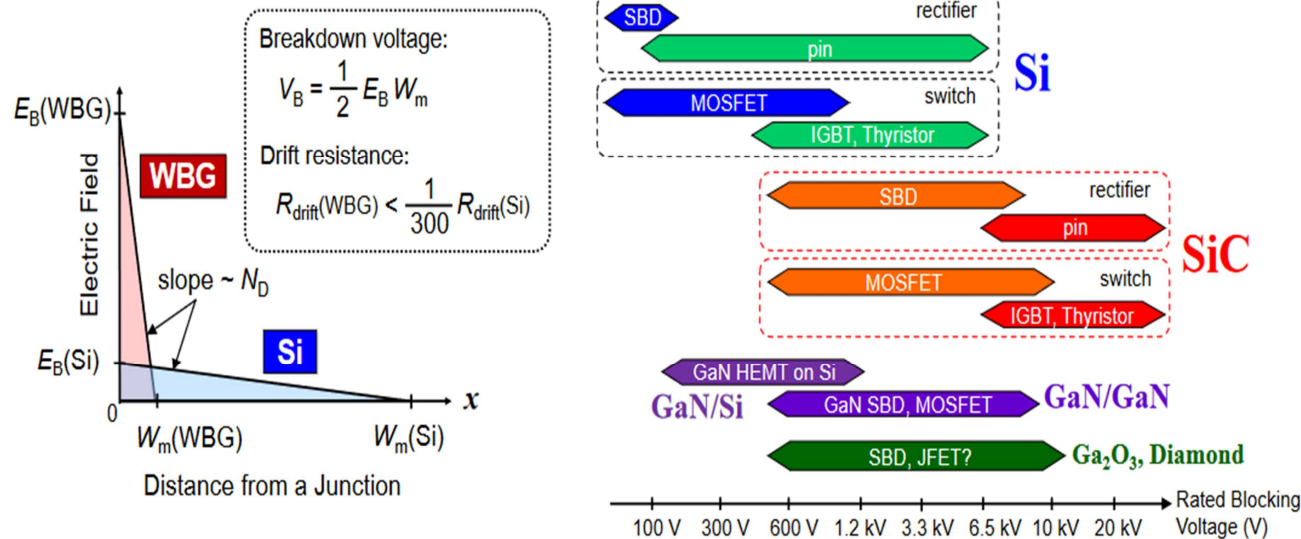


Source : "Power Semiconductor for Efficient Energy Conversion", Gourab Majumdar, Ikunori Takata, Pan Stanford Publishing, 2018, page 13

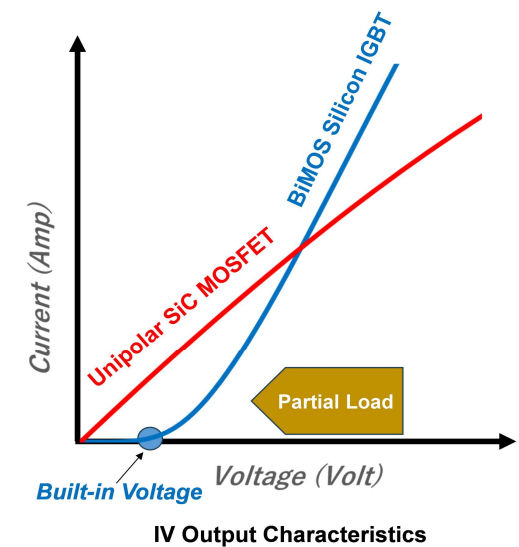
3.4 WBG chip technology

Section 3 of the white paper also explains SiC and GaN in comparison to silicon, indicating that SiC has the potential to grow to \$6.3B in 2027, and GaN to \$2B. Looking at future UWBG devices after 2030, it briefly mentions Ga₂O₃, diamond, AlN, vertical GaN, and their challenges.

WBG Power Semiconductors



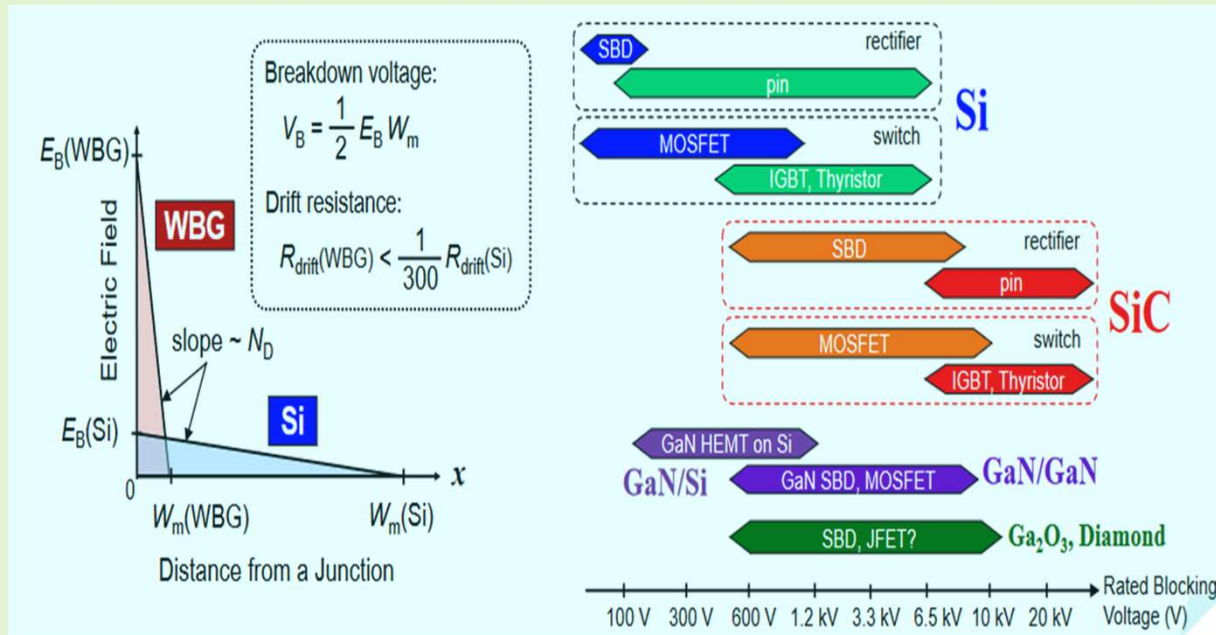
Device characteristic trade-off related to structure and applicability range of WBG power semiconductors (Figure 3-3 of WP)



Merit of power MOSFET at different load current (Figure 3-4 of WP)

(3.4 related) Wide-Bandgap (WBG) and Ultra-Wide-Bandgap (UWBG) Power Semiconductors

Range of applicability



☆ Among the WBG/UWBG semiconductors, SiC, GaN, and Ga_2O_3 , are potential materials for the next generations of devices

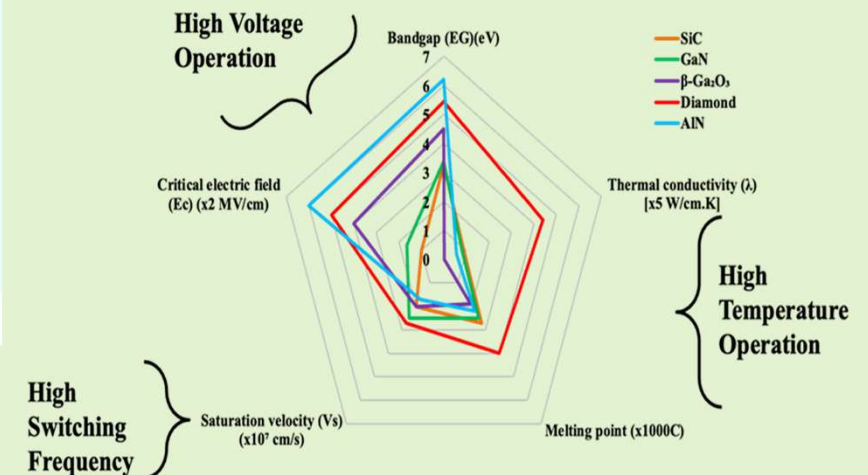
☆ Low drift resistance, allows WBG unipolar devices such as MOSFET and SBD to outperform silicon devices above $BV=300V$

☆ However, both bulk and interface (surface) defects affect the reliability and cost-performance ratio of these WBG devices => material improvement and effective screening procedures are essential

☆ SiC use: Vertically MOSFET is the most effective and widely applied device concept

☆ GaN use: Lateral HEMT is the current choice, with ongoing R&D for vertical types

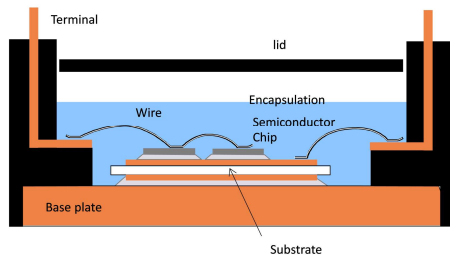
Key physical and electrical properties



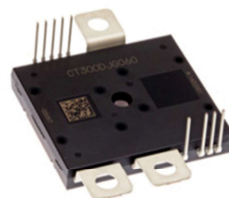
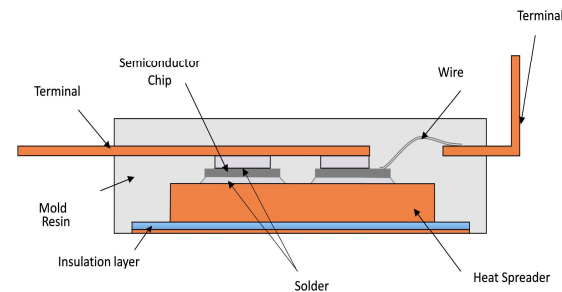
3.5 Module and IPM technologies

Section 3.5 of the white paper introduces industrial modules, mold structures for WBG, and IPM. The module market will grow at a CAGR of 12.8% and reach \$14.8B in 2028.

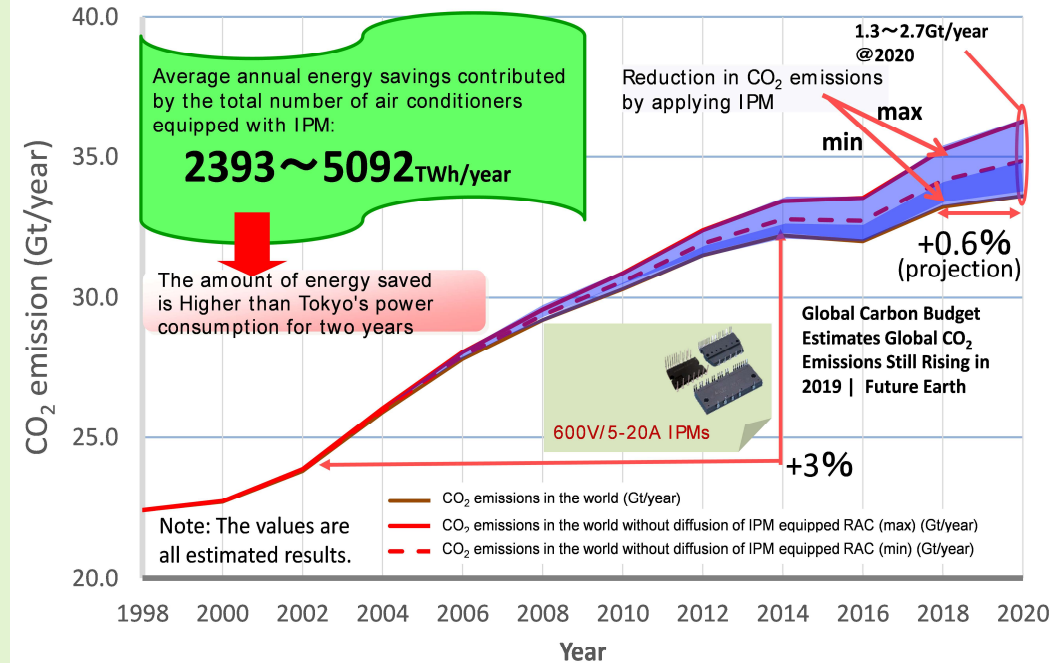
IPM, module technology that smartly utilizes chips



General module structure (Fig.3-7 of WP)



Mold module structure for WBG (Fig.3-9 of WP)



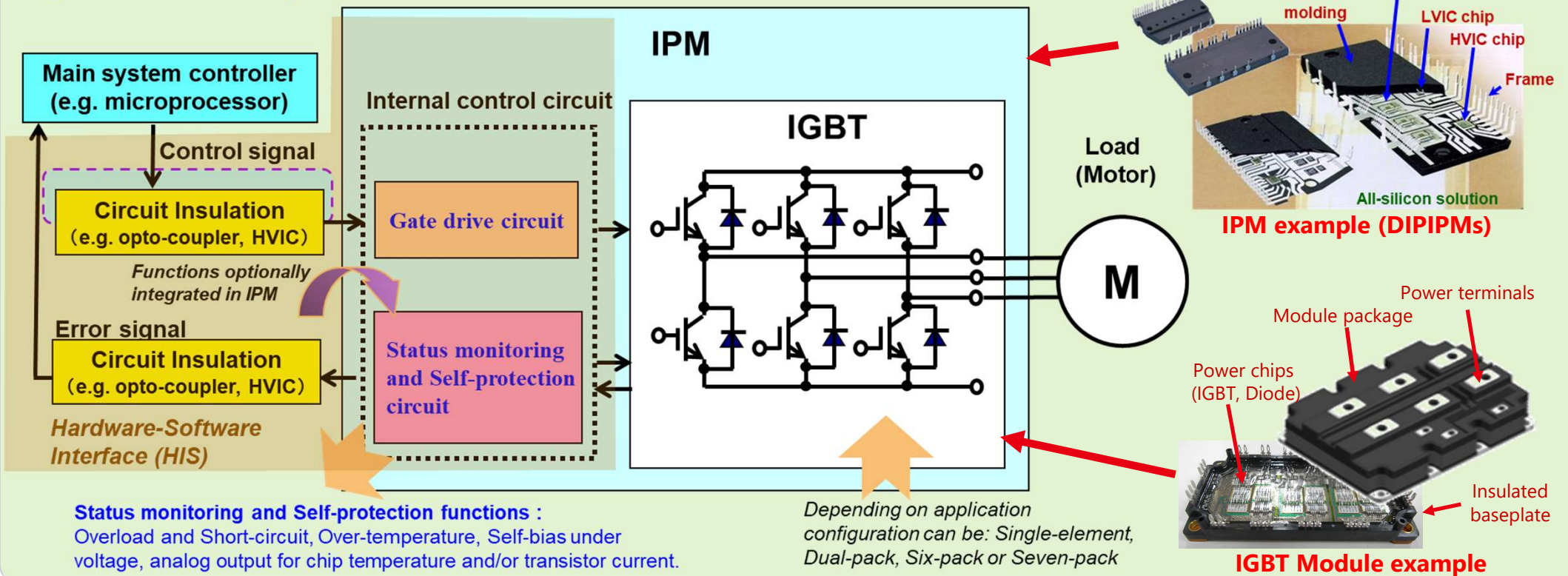
Air conditioner inverter using IPM and CO₂ reduction (Fig.3-8 of WP)

(3.5 related) IGBT Module and Intelligent Power Module (IPM)

Source: Book titled "Power devices for efficient energy conversion" by Gourab Majumdar, Stanford Publication

IGBT Module: IGBT and diode power chips are integrated in multi-chip circuit formation in insulated module packages to meet some specific application purposes.

IPM: Integrates self-drive and self-protection functions in an IGBT module based on an optimized total design.



3.6.1-3 Material supply chain

To realize an energy-wise society, it is important to establish adequate material supply sources that match growing demand. The white paper describes the importance of supply chain.

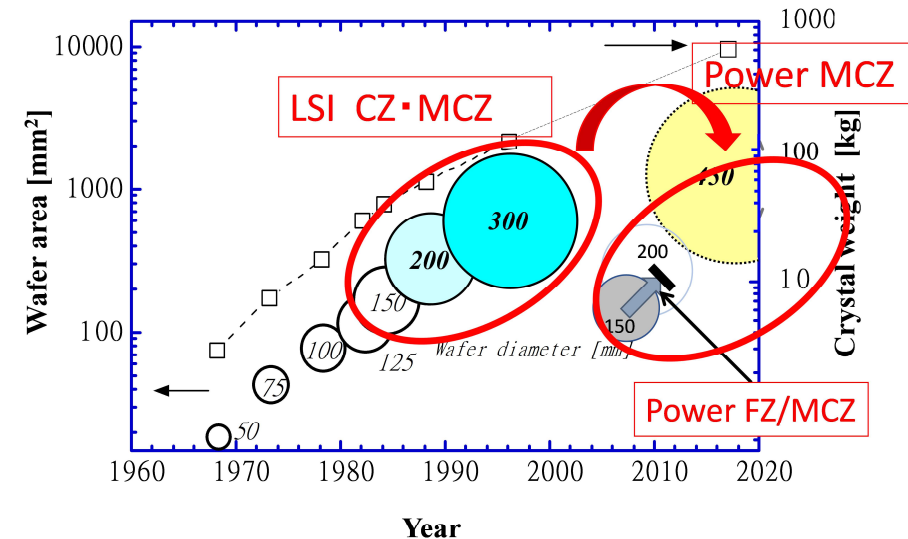
Wafers for silicon, SiC and GaN power semiconductors

1. Wafer for silicon power semiconductors

- In IT applications, it is possible to reduce chip size through miniaturization, but power is not easy due to heat issues, and wafers are moving toward large-scale hospitals.
- Physical and electrical properties of the wafer are important for power (not surface devices)
- Current issues are improving the quality of MCZ, increasing the diameter of FZ (large diameter is MCZ, improving O and C, FZ doping method similar to NTD, etc.)
- In terms of energy, demand for VRE and power transmission and distribution networks is expected to increase, and securing FZ-NTD for high voltage devices that will be required is also an issue.

2. Wafer for SiC/GaN power semiconductors

- SiC demand will grow at a CAGR of 25% from 2021 to 2027, and wafer and epitaxial supply will be a challenge
- The transition from 150mm to 200mm will occur, and bonded wafer technology will also appear
- The sublimation method for SiC is a more difficult manufacturing method than Si, and it is necessary to improve defects including epitaxy.
- JEITA, SEMI, IEC, etc. are working on guidelines and standardization.
- GaN demand will grow at a CAGR of 58% from 2021 to 2027 (chargers, OBC, data centers).
- GaN HEMT forms a GaN layer on a silicon wafer, and has a maximum of 300 mm.
- Due to the difference in lattice constant and thermal expansion coefficient between GaN and silicon, there is a limit to achieving high breakdown voltage.



History of silicon wafers (Figure 3-10 of WP)

3.7-8 Gate driver, LCA

- In addition to the supply chain, gate drivers are important in terms of power electronics.
- LCA considerations will be required in the future.

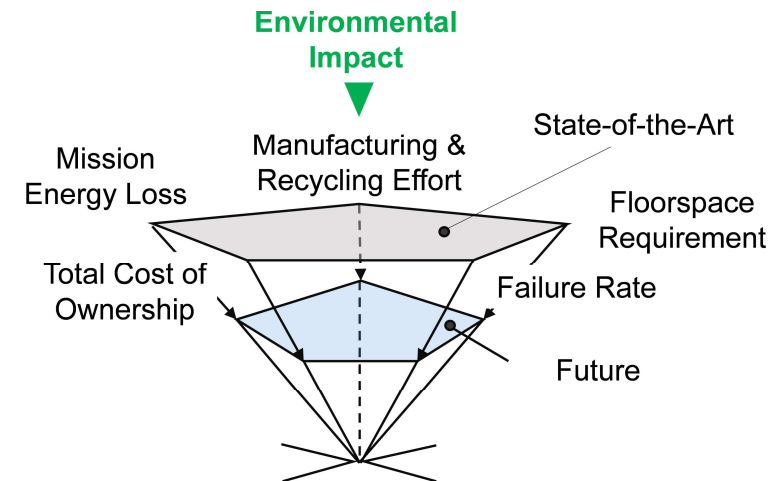
Power module components

1. Gate driver

- Gate driver IC market to grow to \$2.7B from 2021 to 2028 with a CAGR of 8.5%
- Essential component for non-IPM devices/modules
- In the future, we will also combine it with sensors to enable on-the-fly adjustments and diagnostic functions.

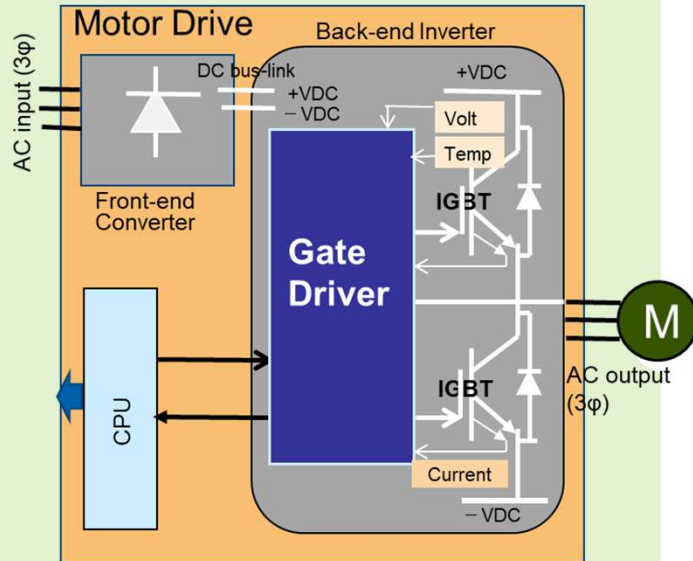
2. Life Cycle Assessment

- LCA is the process of estimating the environmental impact of a product over its lifetime, from materials to use, disposal, and recycling.
- Find improvements through LCA calculations and provide information to customers
 Manufacturing process: Wafer manufacturing, processes, packaging, etc.
 Usage status: consumed electricity
 End of use: Disposal or recycling
- At present, there are few examples of LCA calculations for power semiconductors, and this is a future issue, but due to government policies and other factors, this will become increasingly important in the future.



Trends in Energy Electronics Performance
Parameters (Figure 3-13 of IEC WP)

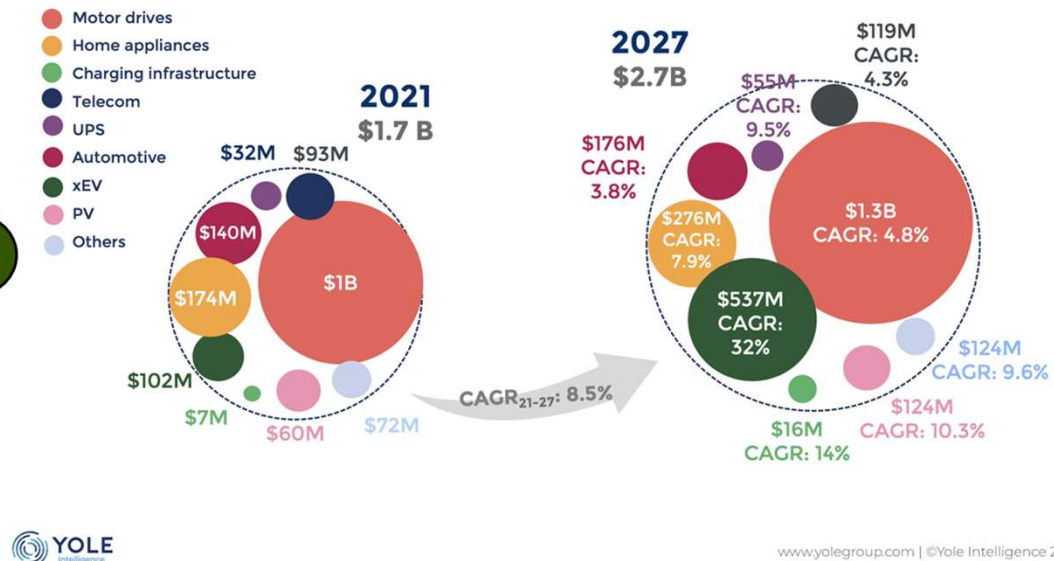
(3.7 related) Gate Drivers



Gate Driver
(HIS using ICS and discrete components
(e.g. ASICs, HVICs and/or Opto-couplers
and/or surface-mounted transformers) on PCBs

2021-2027 GATE DRIVER IC MARKET DEVELOPMENT

Source : Power Gate Driver IC report, Yole Intelligence, 2022



Key enablers for advancement are enhanced diagnostic and monitoring functionalities:

- **Harmonization of the Hardware-Software-Interfaces (HIS)**: Including respecting the different requirements given by the used isolation system (monolithic level shifter, optical, magnetic, or capacitive separation)
- **Guideline of diagnostic and monitoring functions** based on application and power module requirements: Including respecting the requirements for IGBT, SiC MOSFET and GaN HEMT devices such as switching speed, reaction time for protective functions, diagnostic and monitoring cycles, influence of parasitics (e.g., gate loop inductance, commutation loop stray inductance etc.).

4.1-5 Standardization

To date, various organizations have been developing guidelines and standards

Status surrounding standardization of power semiconductors

1. Various organizations are involved in standardization

- Standardization organizations: IEC, JEDEC, JEITA, UL
- Industry: SEMI, AEC, UNIFE, (power semiconductor users)
- Public organizations: national regulatory authorities, IEA
- Technical associations and academia: universities, research institutes, Power America, ECPE

Coordination?

- Users can use it with confidence
 - Users can choose appropriate power semiconductors
 - Shortening time to market (development, certification, etc.)
 - What power semiconductor manufacturers can manage
- ↓
- Through these, the market will grow steadily.

2. Future standardization

- Conditions such as module moisture resistance, combined stress tests, life bottlenecks, and comparisons between manufacturers
- Differences between WBG and silicon (dynamic-on resistance, parameter drift, high dV/dt and high frequency, high electric field, measurement method)
- Changes in the way it is used now, and in the future, increase and change in applications (Different requirements and failure criteria for automobiles, industry, and consumer products, energy-wise apps have long lifespans and are often in harsh environments, new ways of use such as DC energization)
- LCA model and recycling
- On the other hand, as the number of standards increases in line with the increase in applications, the number of power semiconductor products and the burden of certification work will explode.

Standards needs for power semiconductors for an energy-wise society

There is a need for guidelines/roadmaps for power semiconductor standard development that gather a wide range of knowledge from experts and related parties.



Standards organization



Industry



**technical organization,
Academia**



**Policy makers,
Regulatory authority**



- Background: IEC White Paper project
- Highlights of each section of IEC White Paper
- **Conclusion: Recommendations from IEC White Paper**



White paper

Power semiconductors
for an energy-wise
society

Recommendations from IEC White Paper



Policy makers, Regulatory authority

Policy makers and regulatory authorities should act to foster a strong and dynamic ecosystem, including academia and startups, to support technology development and further develop the market.



Industry

The industry should expand the use of power semiconductors and build a stable supply chain to achieve this by utilizing test methods, reliability and certification schemes based on appropriate international standards

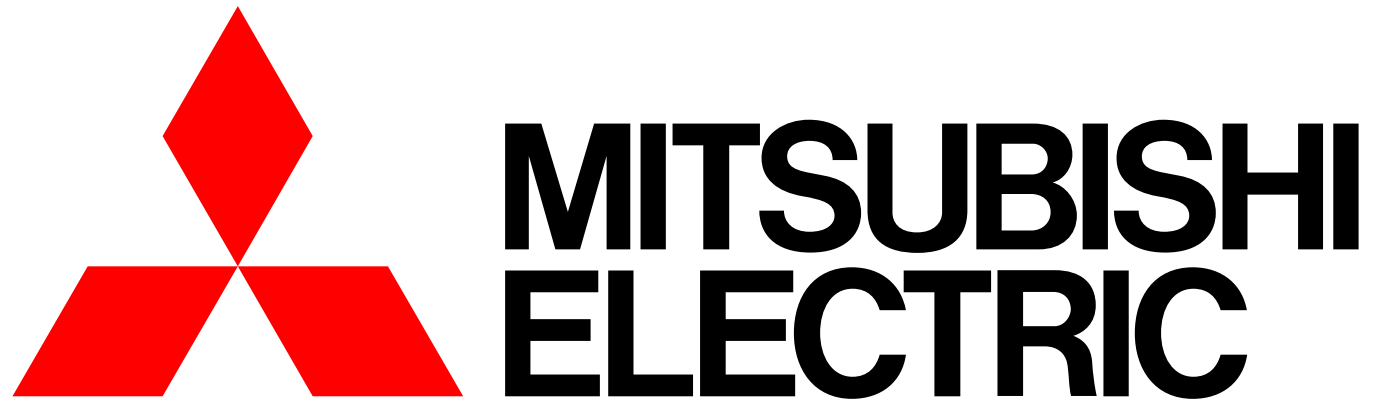


IEC and Standards organization

Standardization organizations should collaborate with diverse stakeholders from industry and academia to contribute to building a balanced value chain in the power semiconductor field.

IEC should strengthen knowledge sharing with organizations that collect and analyze information on power semiconductors.

Activities should be carried out to develop standards and establish a certification system to promote the utilization of technologies related to power semiconductors.



Changes for the Better