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Wide Band Gap Devices in Power Systems

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I. INTRODUCTION

- The power grid is transforming in an unprecedented scale (Renewable energy, Power Electronics, Energy Storage, ...)
- South Australia is leading these transformations
- “Instant” renewable energy generation can be > 100% of the demand !
- “PV systems could produce electricity at a lower price than the grid !”

Major Issues:

- In Australia, coal-fired power stations will reach the end of their technical life by 2040
- Intermittent sources: Change the dynamic power demand-supply balance
  Increasing power quality issues (harmonics, voltage variation, $\Delta P/\Delta t$)
  Reverse power flow (distribution/transmission): operation, protection, security
- Traditional power networks are designed for voltage drops, not for voltage rise.
- **Demand increase** : EV charging loads and air conditioners (in Australia !)
- **Energy gap** likely to come from Wind and PV
- **Reliability** and **cost of energy** !

Great opportunities for the electrical and electronics industry:

- Power quality and efficiency improvements
- Microgrid, EV, Air/Con (DRED) technologies
- Technology development for the grid transformation (converter technologies with WBG)

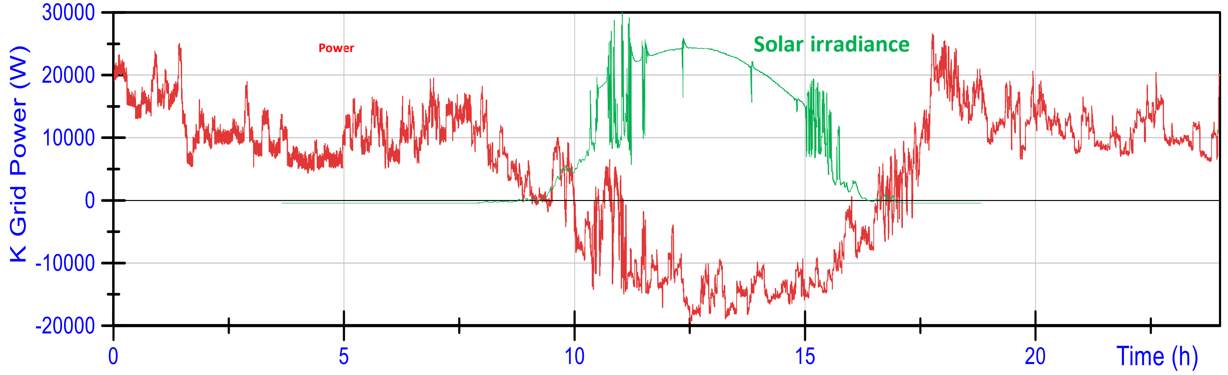
- PV hosting capacity of a given region differs : energy needs of the local load center
  amount of PV supply already connected

- Localised solutions are desirable to mitigate the negative impacts of PV

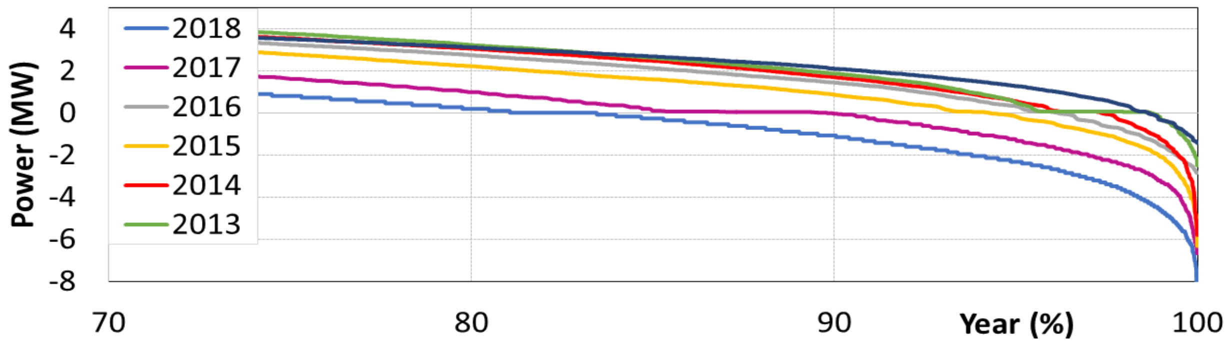
- Various pilot studies have been reported (BSS, VPP..) but no quantified benefits and technically effective network solutions are demonstrated !

Few selected issues associated with intermittent sources and DERs

Reverse power



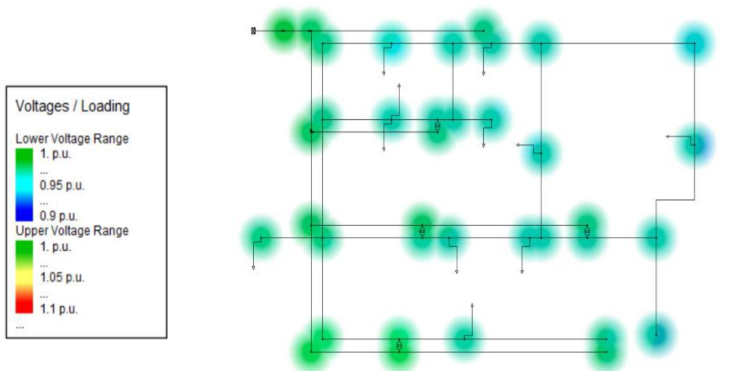
A typical daily power flow in a town with high PV uptake and with the corresponding solar irradiance



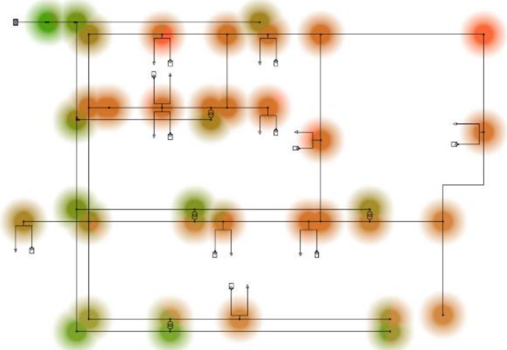
A transmission network level load duration curves over multiple years with increasing reverse power flow

Few Selected Issues Associated with Intermittent Sources and DERs

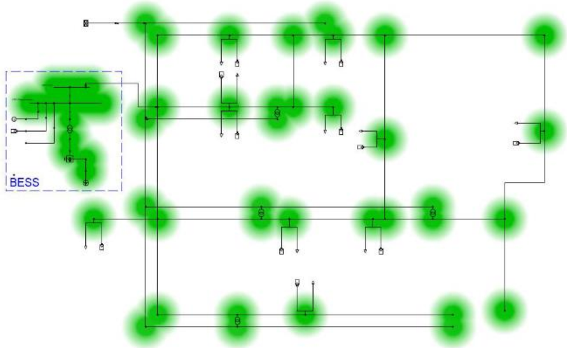
Voltage variations (voltage heat maps) and power losses



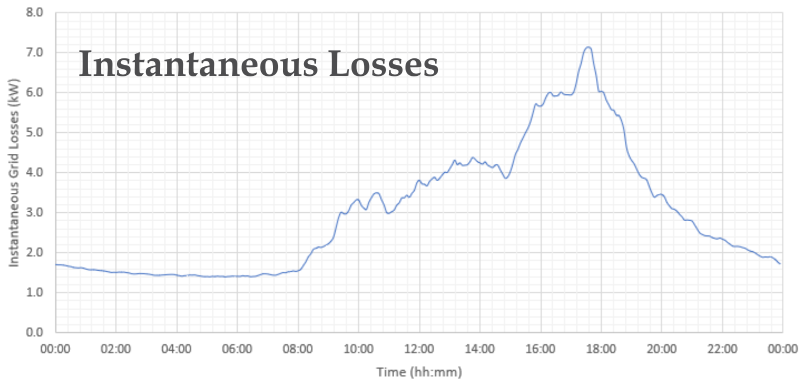
Traditional Grid No PV

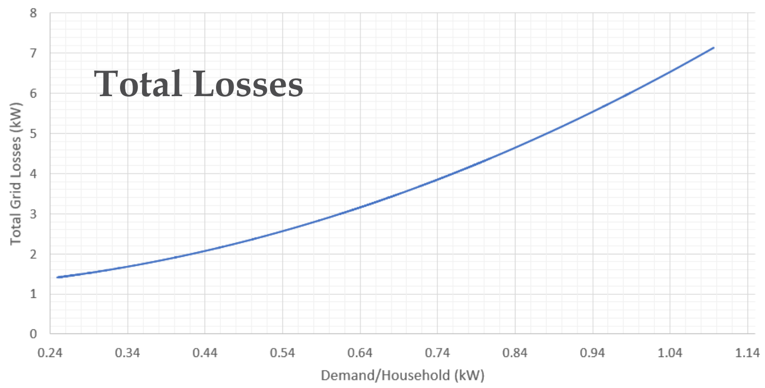


Traditional Grid with PV



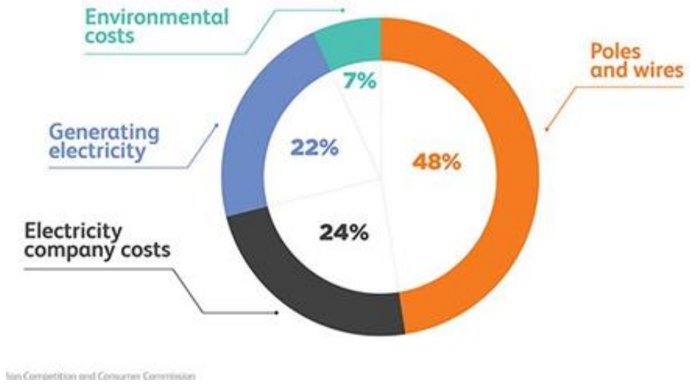
Microgrid with PVs and BESS





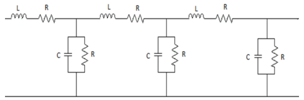
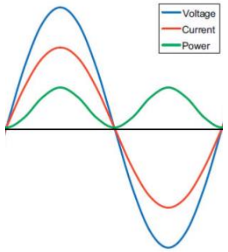
II. GRID TRANSFORMATION !

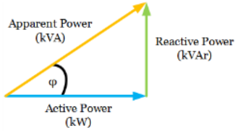
- Power networks are involving increasing level DERs and embedded (on-grid) and off-grid microgrid structures
- Electrical loads are changing (has already changed!)
- Power Electronics drive the renewable energy technologies and DER sources
- The grid is currently in a hybrid stage (as in transportation vehicles!), AC and DC (while DC intermediate stage is increasing)
- Reliability is reducing, energy cost is increasing !

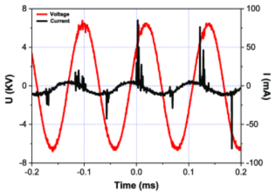


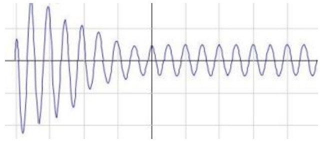
Comparison of AC and DC Supplies



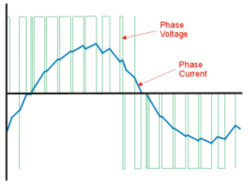






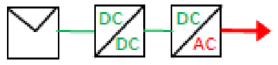
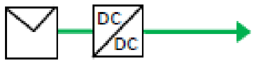
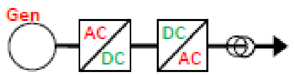
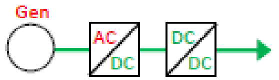
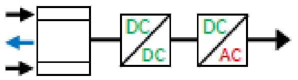
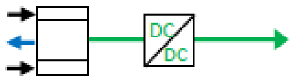
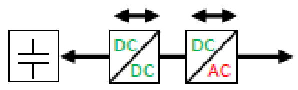
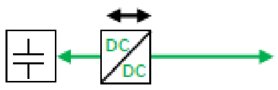
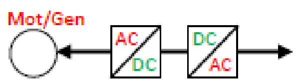
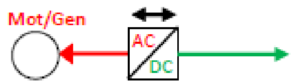
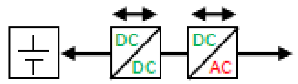
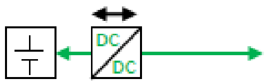
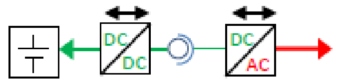
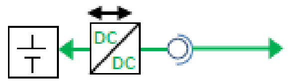




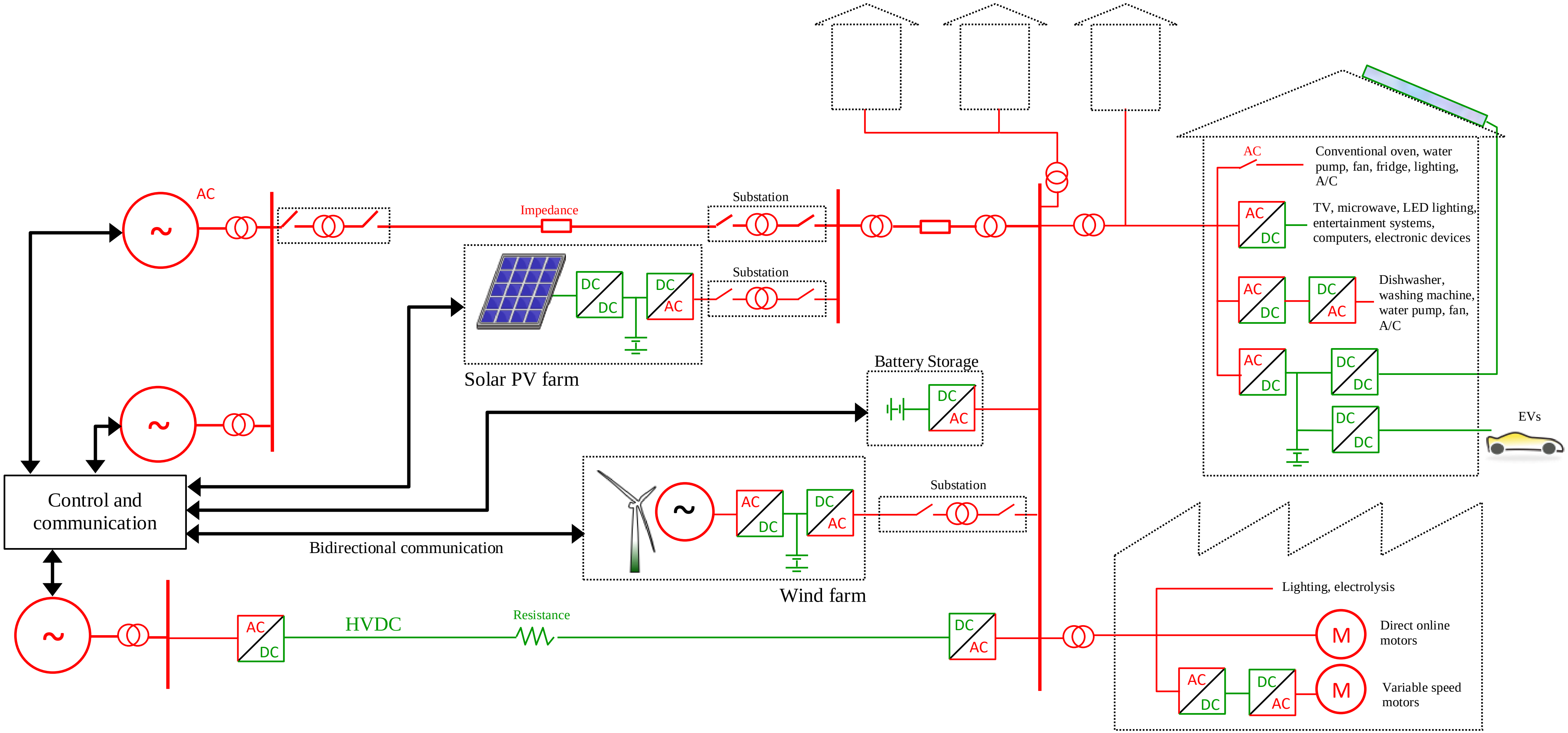
Undesirable features of AC	Factors that favour DC
Regulation issues (voltage, frequency and phase)	Changes in "existing and emerging generator /load types" (camouflaged or genuine DC)
Synchronisation and time delay	Wide utilisation of Power Electronics
Impedance and reactive power	Demand for high efficiency
4-quadrant control	Demand for accurate control
Power quality issues including harmonics	Needs for multiple DC voltage levels
Large initial currents (in motors, lines and transformers)	
Unbalance issues and sequence impedances (positive, negative, and zero)	
Skin effects and losses	
Inductive and capacitive coupling, and induced voltage	
Limited stepped-regulation, unidirectional power flow	
Multiple T/D lines and exposure to environmental factors	
Difficulty to integrate to DC (such as renewable energy)	

Embedded modern generation sources and converter topologies

Embedded Modern Generation Sources	Converter Topologies for AC Grid	Converter Topologies for DC Grid
Solar PV		
Wind Generators		
Fuel Cells		
Supercapacitors		
Flywheel systems		
Stationary Battery Storage Systems		
EV to Grid		

Basic structure of the existing power grid (AC and DC, hybrid)



III. Wide BandGap Devices in Power Electronics

- The driving force of the grid transformation is Power Electronics (switches, converters)
- PE aims to address high efficiency (low loss), high power density (smaller/lighter), reliable systems !
- Higher efficiency also results in :
  - reduced energy consumption
  - less heat hence increased insulation and system life
  - less cooling requirements (smaller fan, smaller space for heat-sinking)
  - reduced air conditioning requirements in enclosed spaces (such as in large converters, data centres and battery storage systems)
  - higher short term overloading capacity

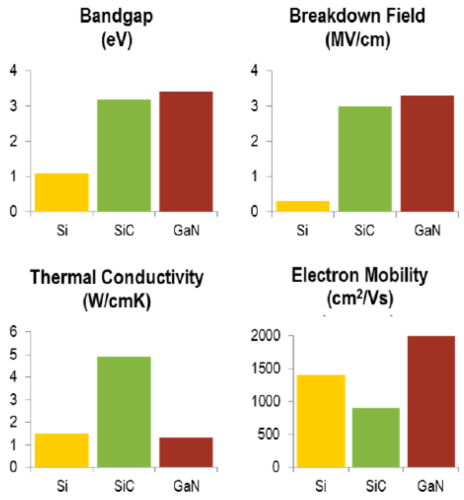
Wide bandgap (SiC and GaN) devices

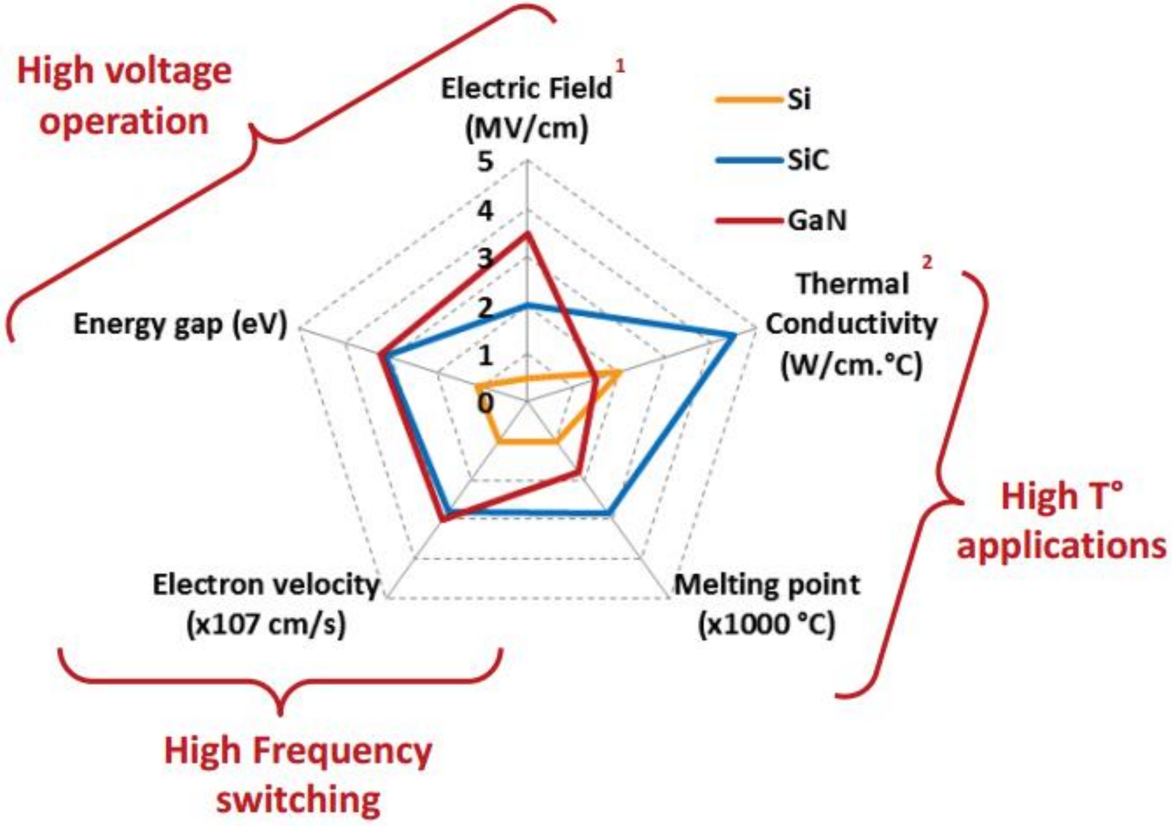
- The use of WBG devices in Power Electronics solutions has shown a huge increase specifically in a wide spectrum of power system applications
- Driving forces are : energy saving, size reduction, system integration and improved reliability

- WBG (1.1 eV for Si and 3.26eV for SiC)
- Status : GaN HEMT devices (600ns at 350V)
  SiC devices (400V -1700V and 1A-325A)

- Desirable characteristics of WBG :
  Higher operating temperatures (smaller heatsinks, smaller die sizes, lower costs)
  Faster switching speed (reduced size of passive element but potential for EMI problems !)
  Higher dv /dt and di/dt ratios (30-50kV/µs and ~1kA/µs, potential sensor/measurement issues!).
  Hence ! Integrated , module based solutions !

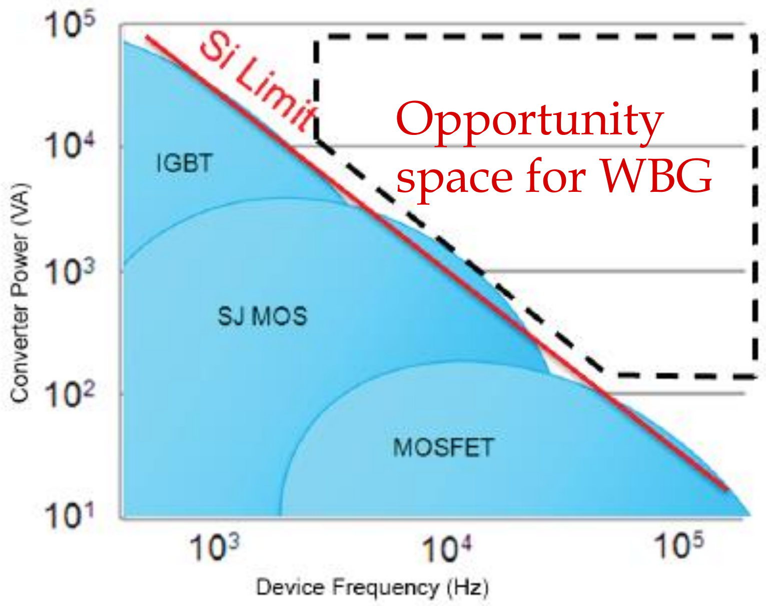
Si versus SiC and GaN

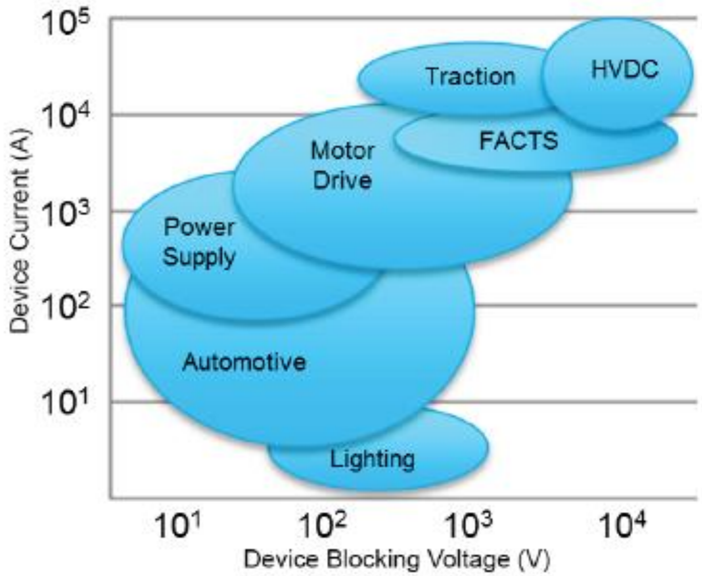




650V/60A
Si (TO-247) vs GaN

Converter Power versus Switching Frequency and Application Areas





(From ARPA-E Report: Wide Band-Gap Semiconductor Based Power Electronics for Energy Efficiency)

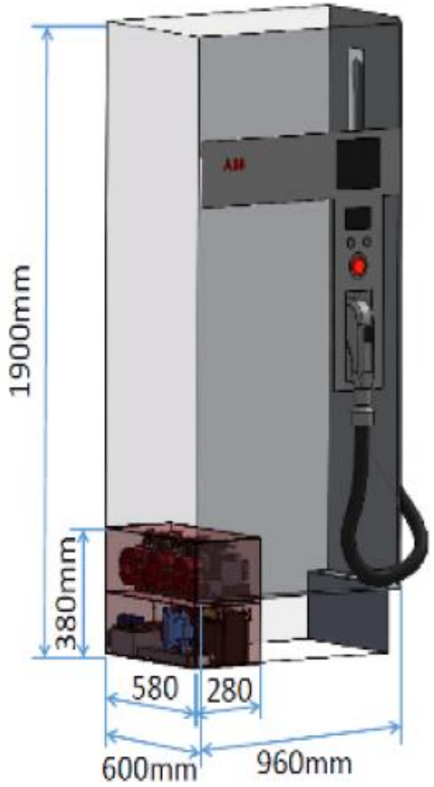
Physical characteristics of Si and few WBG semiconductors

Property	Si	GaAs	6H-SiC	GaN	4H-SiC	Diamond
Eg (eV)	1.12	1.43	3.03	3.2	3.26	5.45
Dielectric constant	11.9	13.1	9.66	9	10.1	5.5
Electric breakdown field (kV/cm)	300	400	2500	2000	2200	10000
Electron mobility (cm^2/Vs)	1500	8500	500	1250	1000	2200
Hole mobility (cm^2/Vs)	600	400	101	850	115	850
Thermal conductivity (W/cm K)	1.5	0.46	4.9	1.3	4.9	22
Saturated electron drift velocity (10^7 cm/s)	1	1	2	2.2	2	2.7

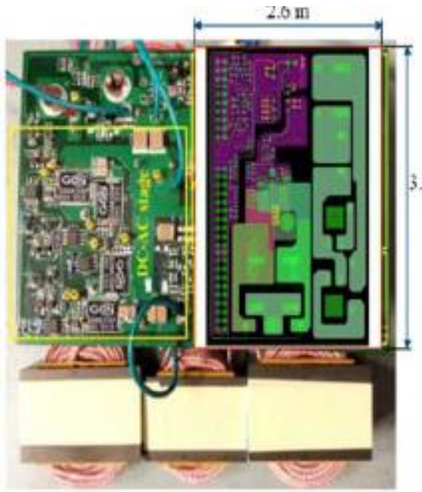
(From L. M. Tolbert et al, http://web.eecs.utk.edu/~tolbert/publications/iasted_2003_wide_bandgap.pdf)

Volume Reduction and Efficiency Increase

(In 2016)

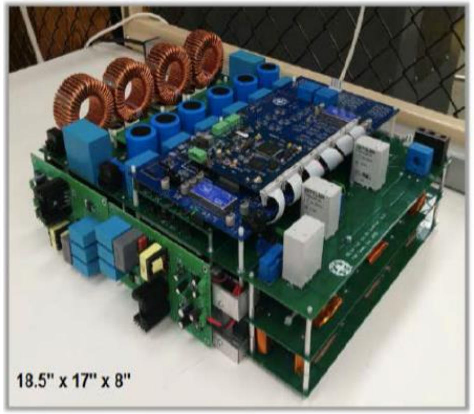


Lukic – MV Fast Charger
10 x size reduction;
4x weight reduction
Cheaper Installation



Ayyaner
Transformerless
Micro inverter
12.8 W/in3

Husain/Hopkins – 55kW inverter for EV
3X denser than Toyota Prius
12.1 kW/L close to 13.4 kW/L DOE 2020 Goal



Efficiency: ≥ 98% Power density: ≥ 8 W/in³ ≥ 1 kW/kg

Li - Gen-1 50 kW Silicon Carbide Based
Transformerless Photovoltic Converter
98% Efficiency, 8 W/in3

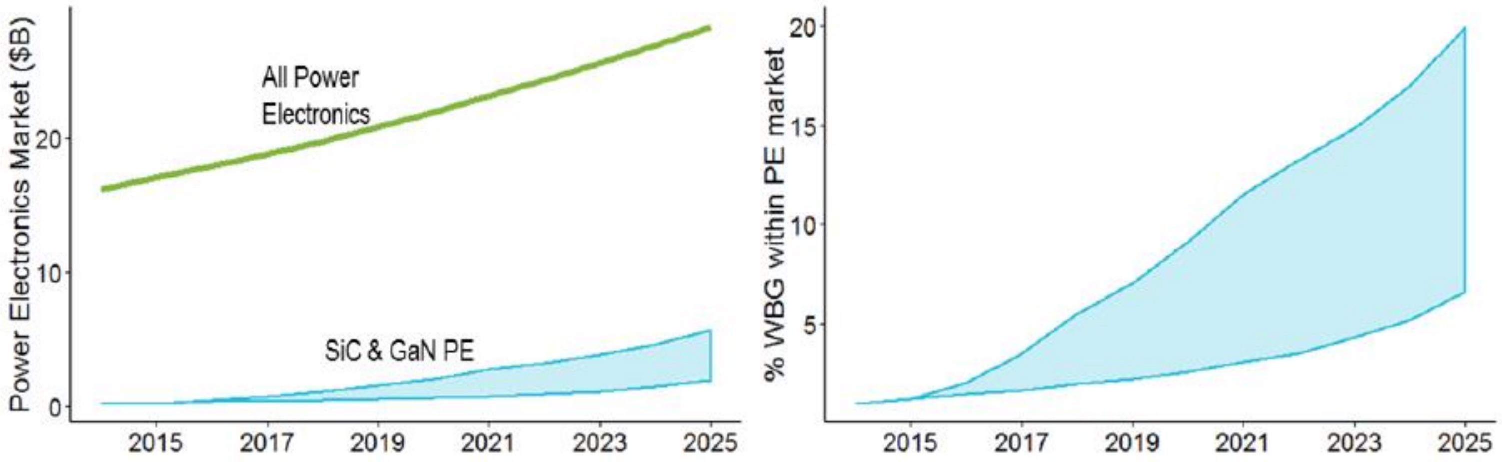
Power America, 2016

(In 2019)

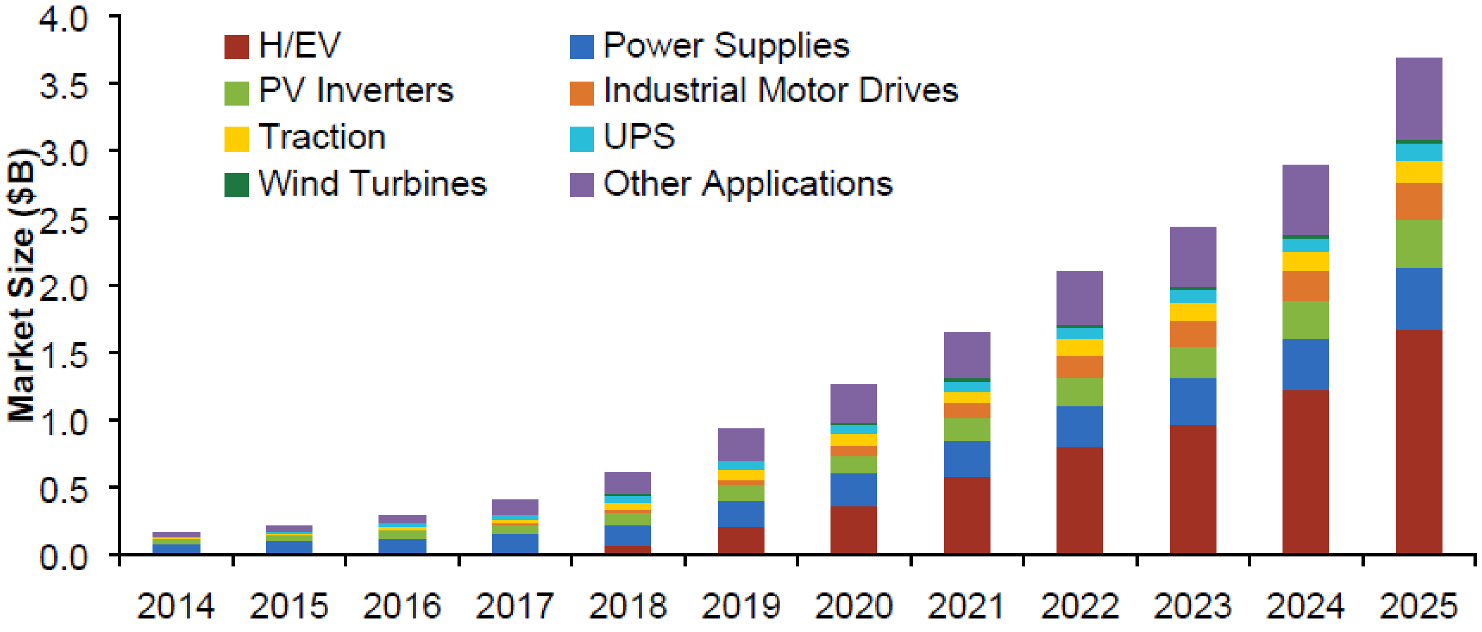
200kW Traction Inverter
with Power Density
of 60kW/L

FREEDM: RESEARCH TO REALITY, 2019

WBG semiconductors within the Power Electronics market by revenue and percentage



Annual growth of WBG market by Application



IV. POTENTIAL WBG DEVICE APPLICATIONS

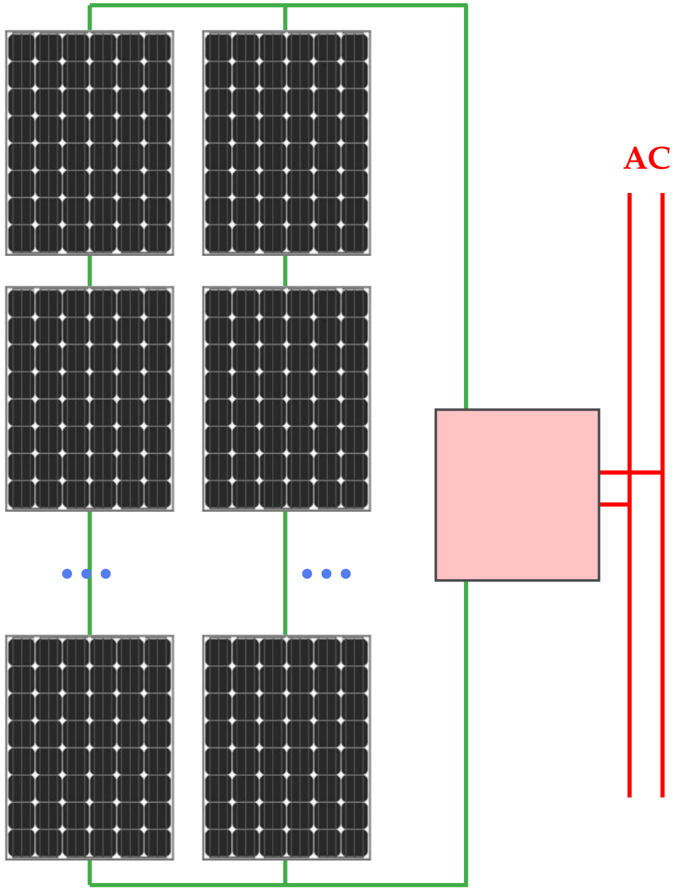
WBG devices will replace present Si devices once the cost drops and modularised solutions offered
PCB layout and gate-drive parameter design needs attention including measurement and protection

The perfect application for WBG devices are:

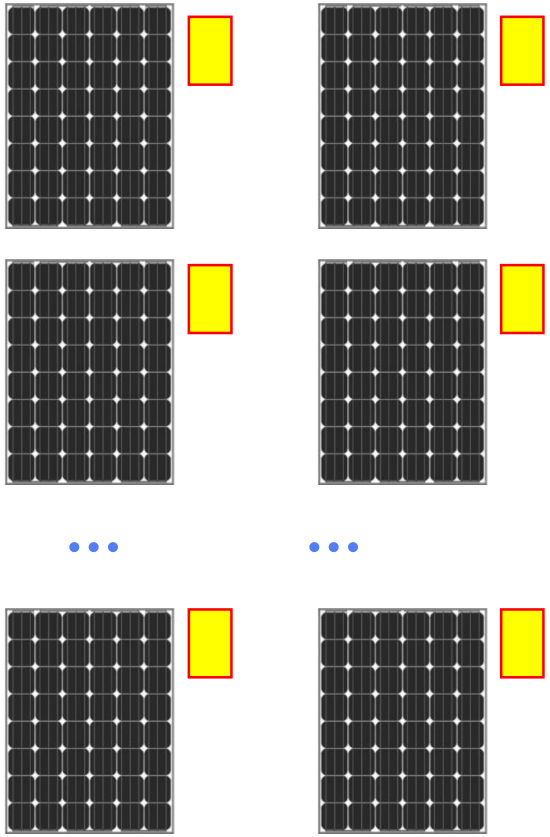
Battery chargers are in vehicle
BSS
PVs
Renewable energy technologies
Motor drives
Power supply applications

IV. POTENTIAL WBG DEVICE APPLICATIONS

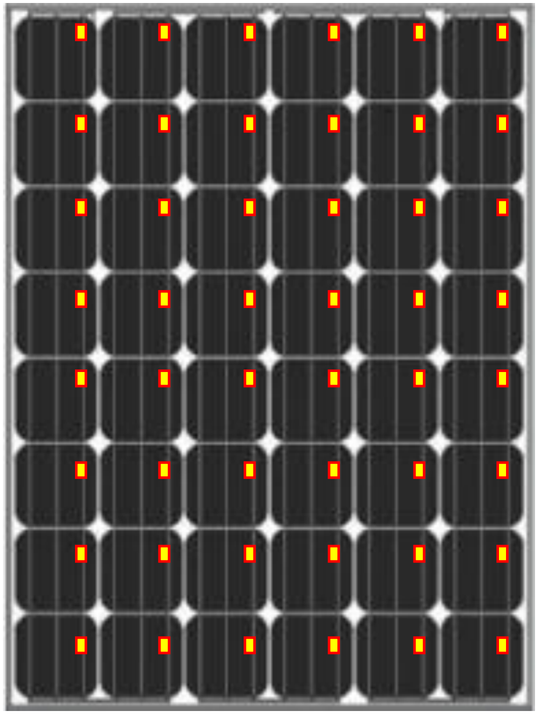
PV Array with String Inverter



PV Structure with μ-Inverter



WBG in Future PV Panels



With WBG DC/DC converters

In EV Chargers

EV Charger Categories

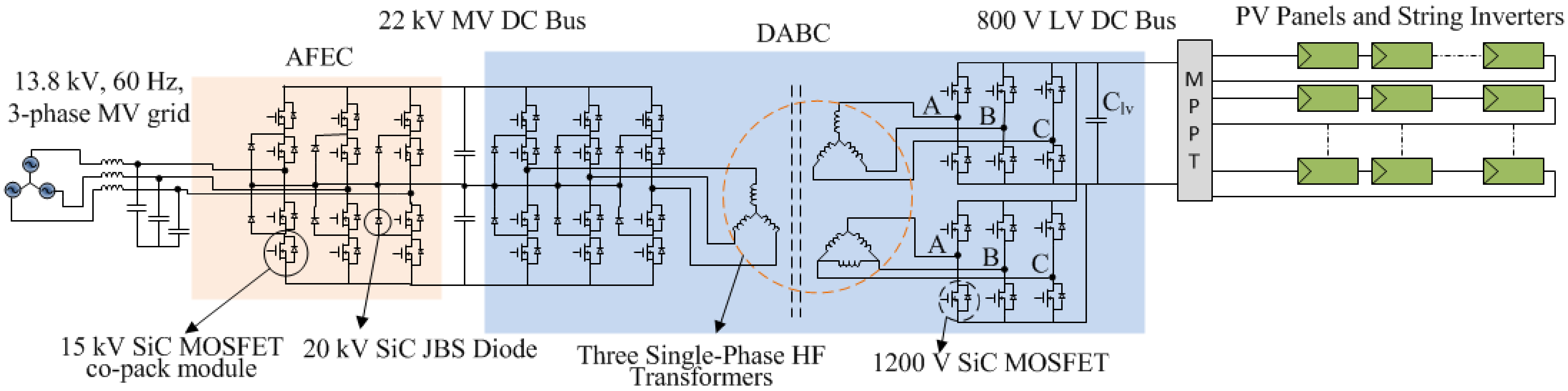
- Single-phase /Three-phase
- On-Board/Off-Board
- Isolated/Non-isolated
- Unidirectional /Bidirectional (V2G, G2V)
- Conductive /Inductive & Wireless

Type	On Board Charger	Inverters & HV Converter	LV DC-DC Converter
Power	~3.3 kW	12 – 400 kW	1 – 10 kW
Input V	120 – 240 V	200 – 400 V	200 – 400 V
Output V	200 – 400 V	100 – 650 V	12 – 48 V
Si Efficiency	85 – 93%	83 – 95%*	85 – 90%
SiC Efficiency	95 – 96%‡	96 – 97%*	96 – 99%
GaN Efficiency	94 – 98%‡	No data	95 – 99%‡
Power Electronics	600 – 900V Discrete	600V – 1.2kV Module or Discrete	600 – 900V Discrete
HEV	X	√	√
PHEV	√	√	√
BEV	√	√	√

From ORNL/TM-2017/702: Wide Bandgap Semiconductor Opportunities in Power Electronics

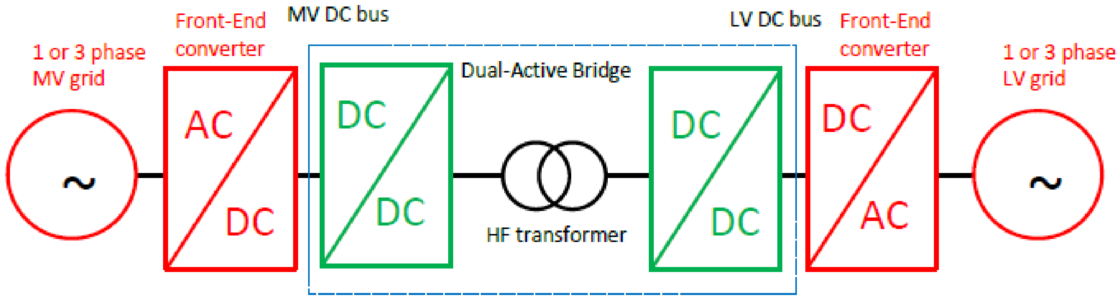
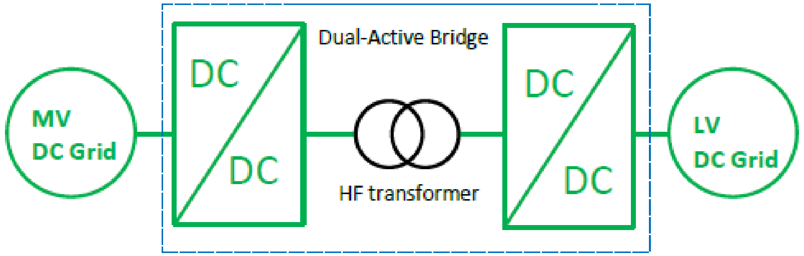
FAST On-Board CHARGING ! 3-Phase, High Power, @ 2-3 C Rate

SiC 10-20 kV devices can reduce the system size in renewable energy applications more than 5x, while offering power and voltage support functions



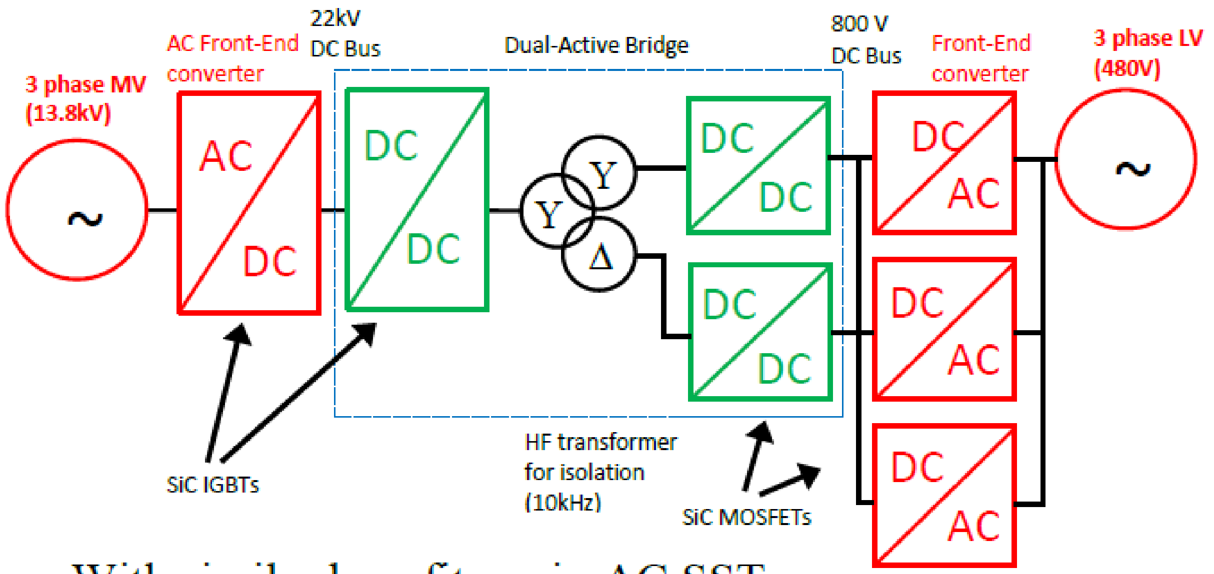
By Subhashish Bhattacharya (North Carolina State University)

WBG Devices in Utility Scale Applications

Solid State Transformers (SST) for AC Grid (Reference to conventional transformers)	**Solid State Transformer for DC Grid (DC SST)** (Reference to AC SST)
	
• Smaller volume and weight • Improved efficiency and reduce cooling requirements • Bi-directional power flow • Improved power quality (unity power factor, harmonic elimination) • Voltage regulation by reactive power control if a battery storage capacity is added on the DC bus. • Flexibility in control also as a AC circuit breaker • Renewable energy integration with AC or DC links • EV chargers can be connected to either MV or LV sides • But more complex control and higher processing power required	• Much simpler hardware and controller, reduced processing power, higher efficiency, greater power density and reduced footprint. • This is the basic building block in SSTs (or DC-DC Transformers). Their input sides and output sides can be connected in series to obtain much higher voltage levels in HV applications (such as in HVDC). • It can be used as DC Circuit Breaker • As various control functions added, it is named as "Smart Transformer"

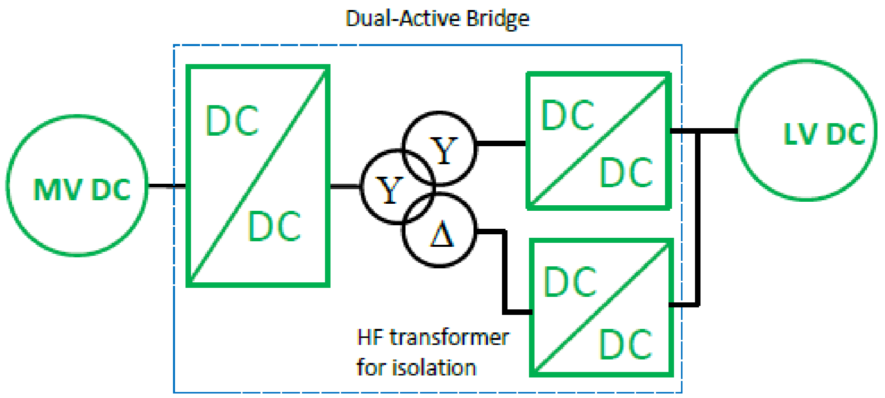
WBG Devices in Utility Scale Applications

Transformerless Intelligent Power Substation (TIPS) for AC Grid (Reference to conventional substations)



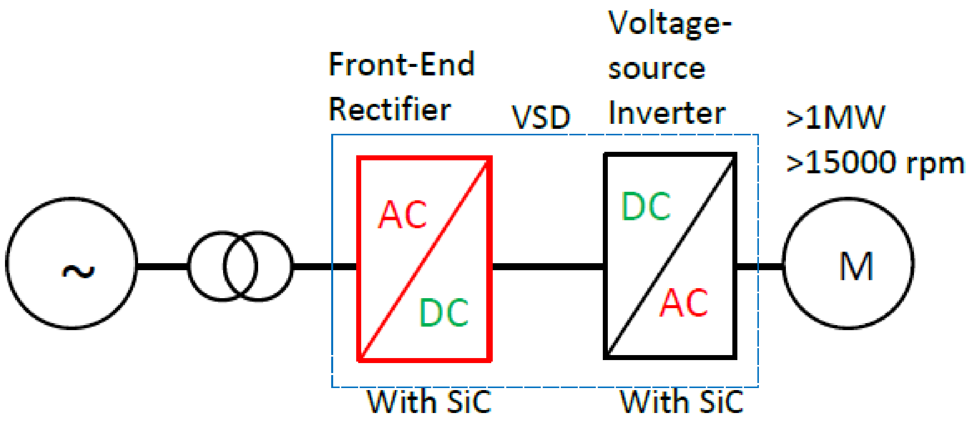
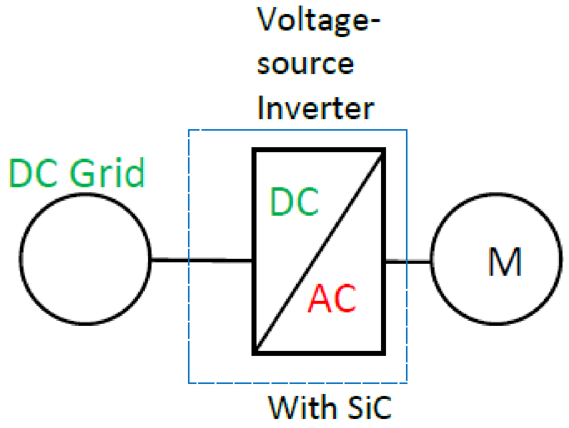
- With similar benefits as in AC SST
- Isolated DC Microgrid can be added (using an isolated output of the transformer with a DC/DC converter)

Transformerless Intelligent Power Substation in DC Grid (DC TIPS) (Reference to AC TIPS)



- Similar improvements as in DC SST benefits as in AC SST.

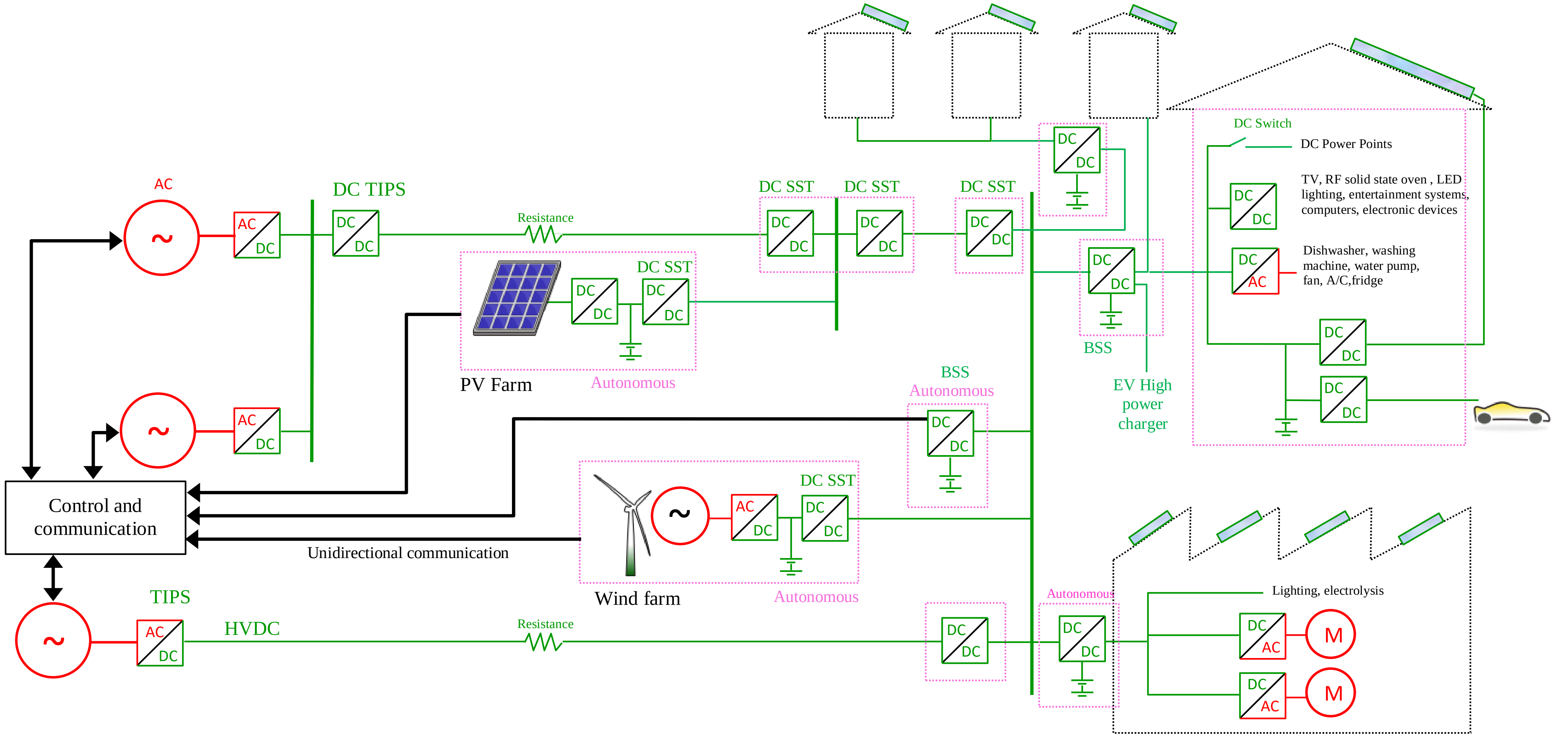
WBG Devices in Utility Scale Applications

Variable Speed Motor Drives for MV Motors in AC Grid	VSDs for MV Motors in DC Grid
	

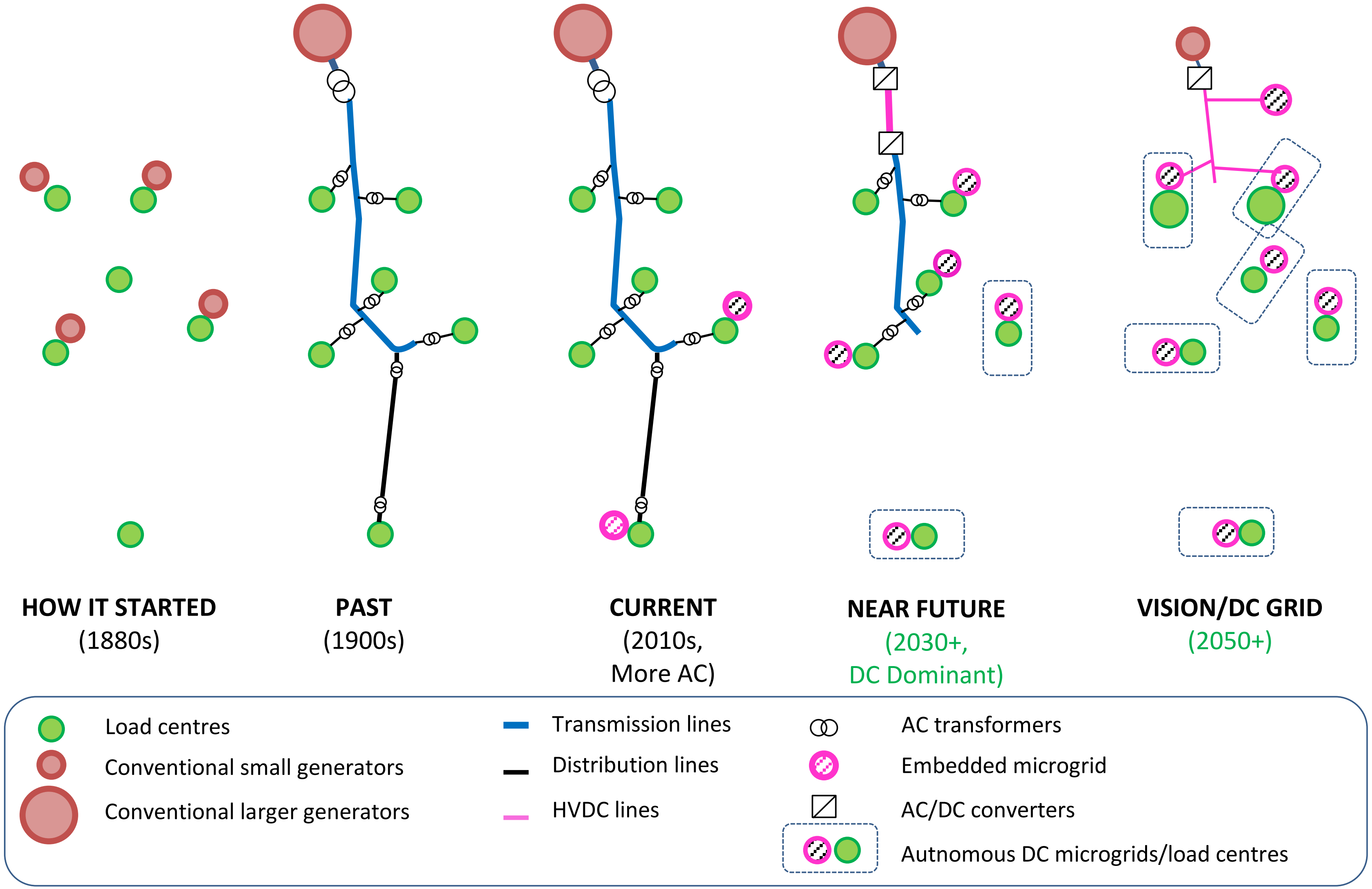
V. CONCLUSIONS

- WBG switches have the potential to revolutionize the field of Power Electronics, hence the entire power system components
- They will allow on-board high-power DC charging for EVs, and V2V, V2G power transfer
- They are likely to drive a much greater transformation (AC to DC !)

Basic components and communication structure of the future grid

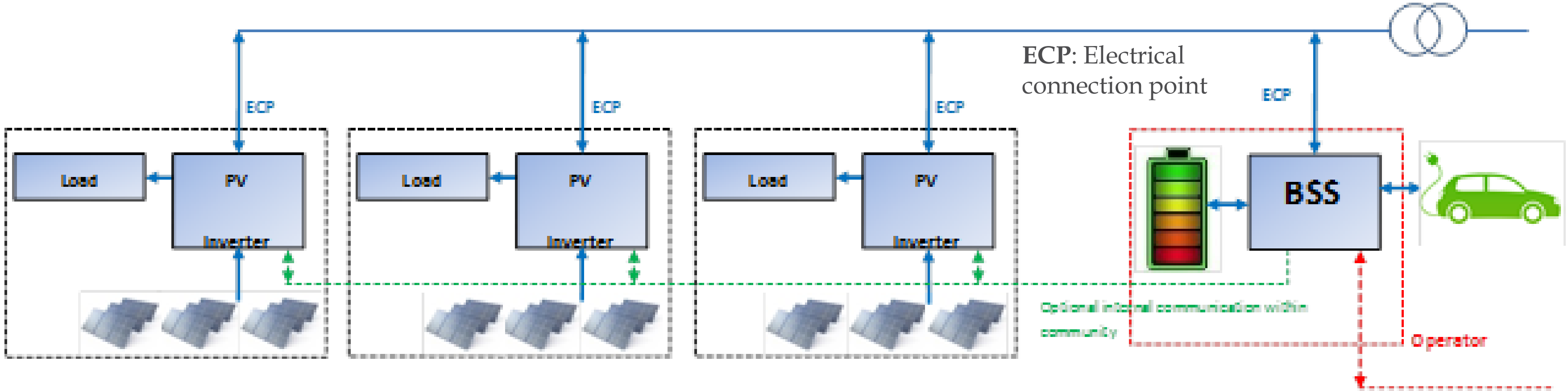


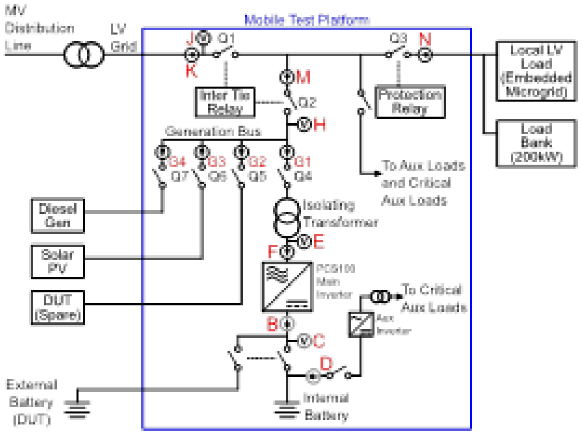
An overview of the grid transformation timeline



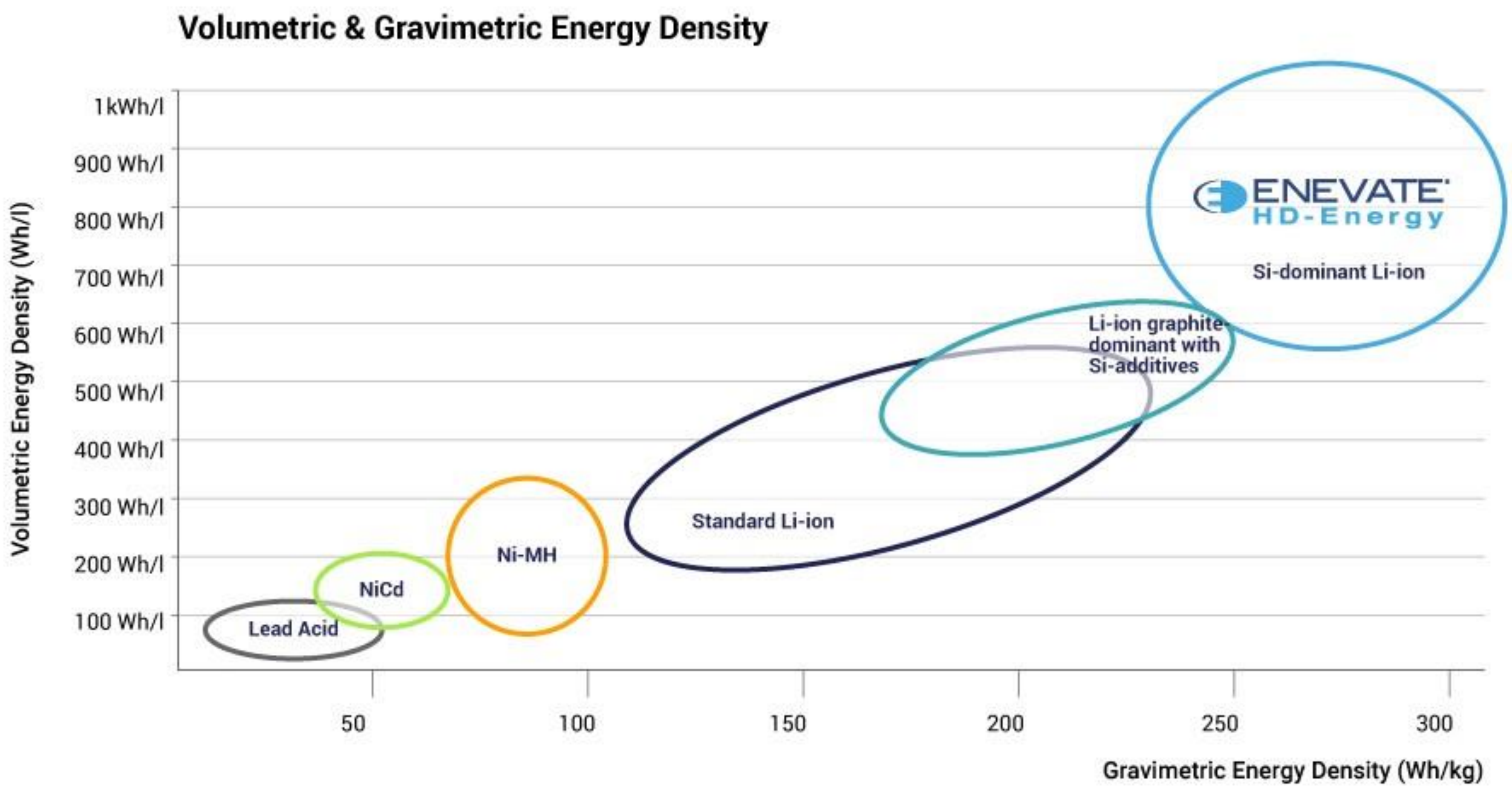
COMMUNITY LEVEL BSS AND BENEFITS

The system architecture of a clustered/community level BSS with a high power EV charger.





The single line diagram of a three phase and flexible BSS unit that can form the community level energy storage


Volumetric & Gravimetric Energy Density
1kWh/l
900 Wh/l
800 Wh/l
700 Wh/l
600 Wh/l
500 Wh/l
400 Wh/l
300 Wh/l
200 Wh/l
100 Wh/l
Volumetric Energy Density (Wh/l)
ENEVATE
HD-Energy
Si-dominant Li-ion
Li-ion graphite-dominant with Si-additives
Standard Li-ion
Ni-MH
NiCd
Lead Acid
50
100
150
200
250
300
Gravimetric Energy Density (Wh/kg)