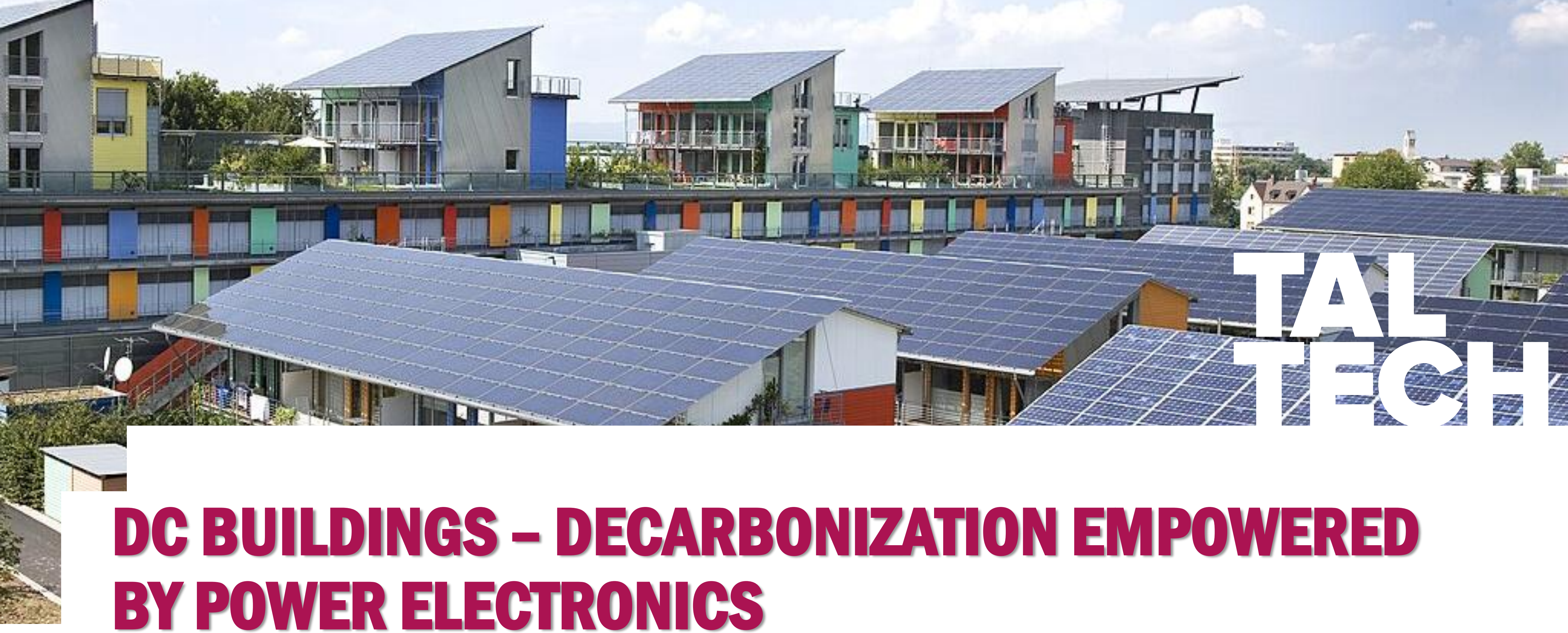


DC BUILDINGS – DECARBONIZATION EMPOWERED BY POWER ELECTRONICS

Dmitri VINNIKOV
Andrii CHUB
Power Electronics Group
Department of Electrical Power Engineering and Mechatronics
Tallinn University of Technology

TAL TECH

Centre of Excellence in Energy Efficiency

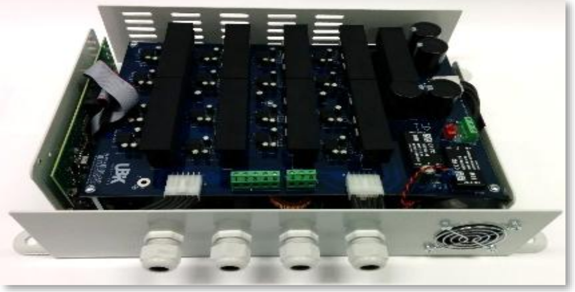
WHERE ARE WE FROM

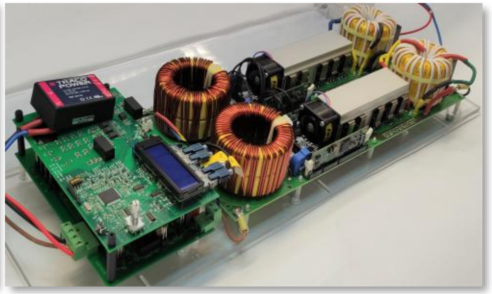
ESTONIA - A Destination for Tech Lovers
TALLINN - The Best-Preserved Medieval City in Northern Europe

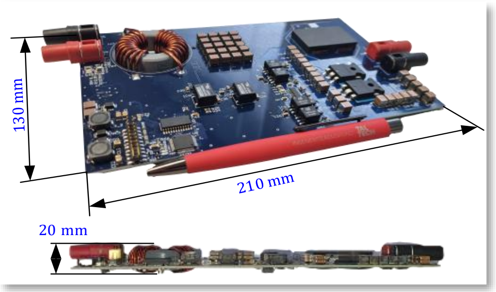
- *Population:1.35 million*
- *Currency: Euro*
- *World's most digitally advanced society*
- *Estonia leads Europe in startups, unicorns, investments per capita*

POWER ELECTRONICS GROUP OF TALTECH

LARGEST RESEARCH CENTER FOR APPLIED POWER ELECTRONICS IN BALTIC STATES







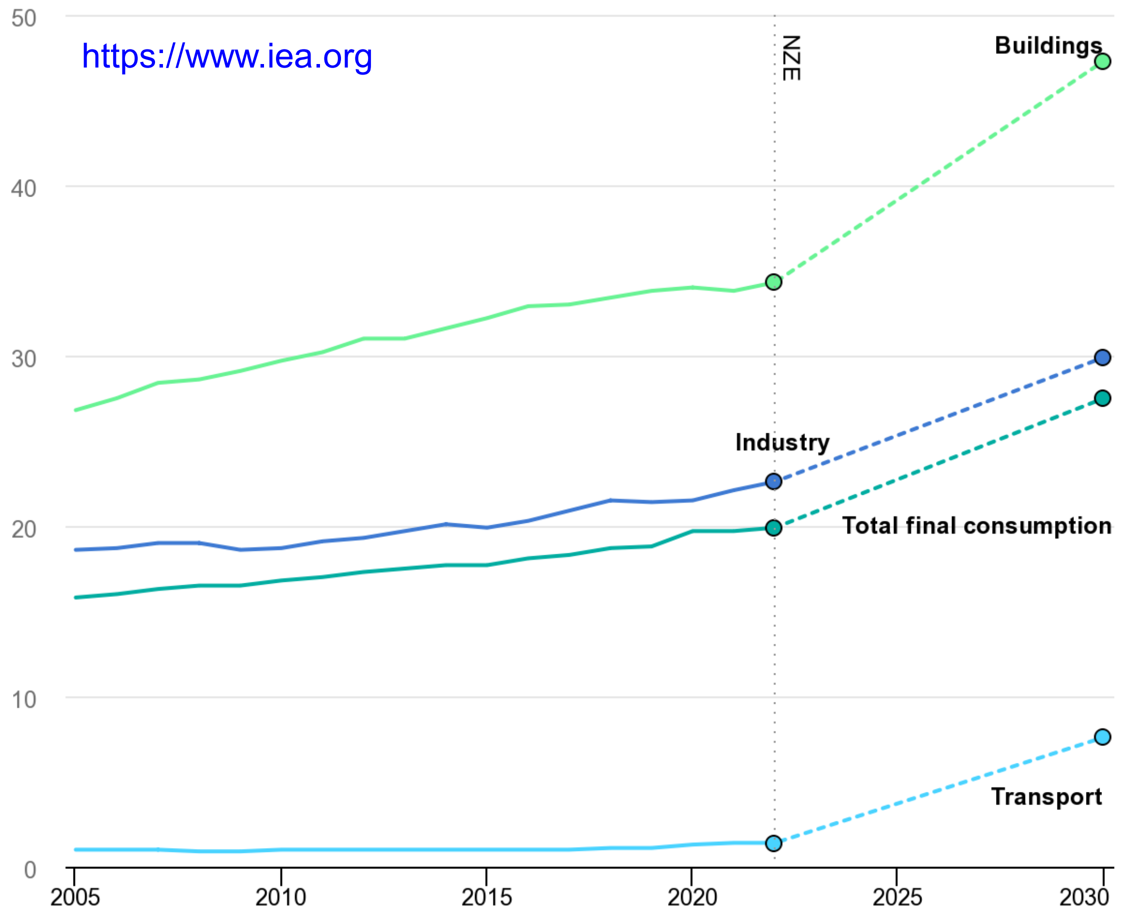
THE CHALLENGE WE ADDRESS

ENHANCEMENT OF ENERGY PERFORMANCE OF BUILDINGS

TAL TECH

TOWARDS 2050 NZE PATHWAY (EU GREEN DEAL)

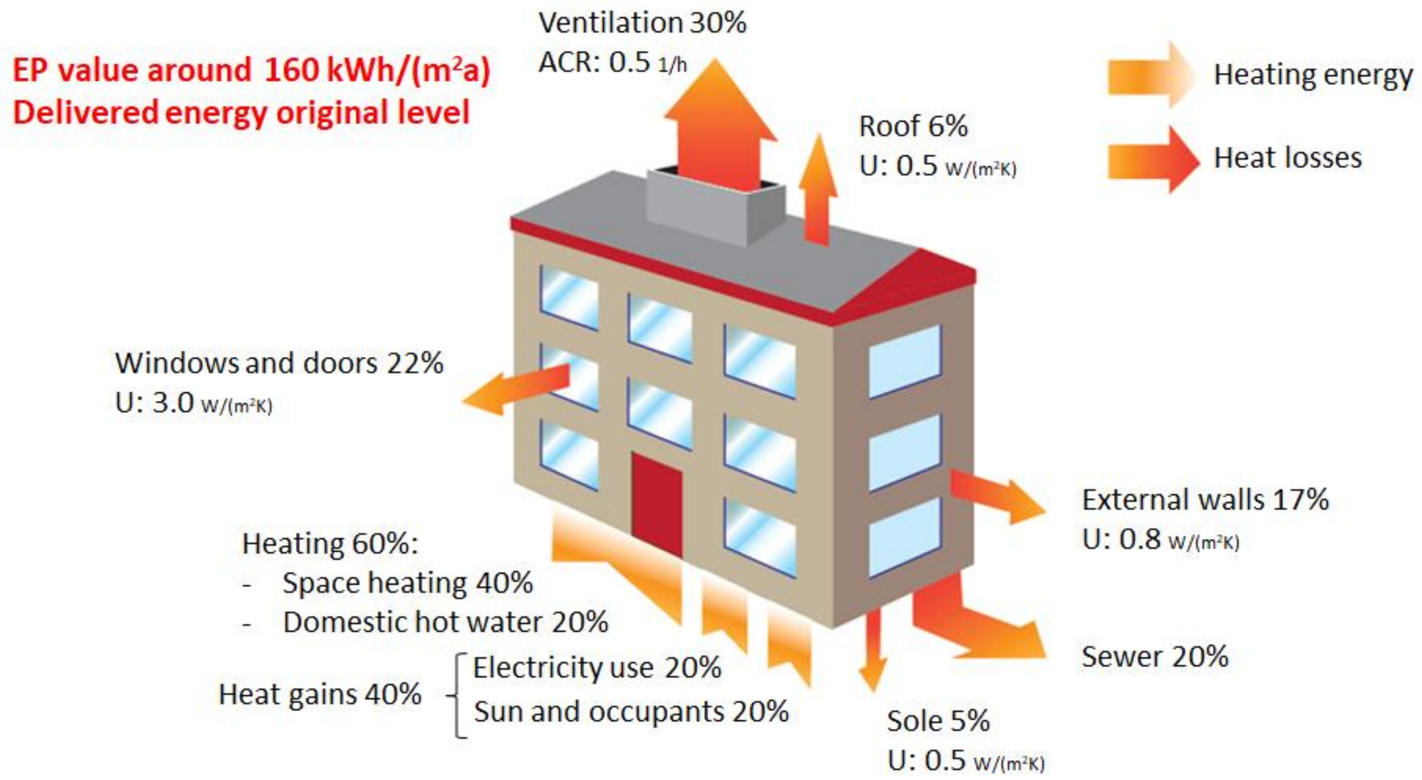
- *By 2050 the EU aims to become the* ***world's first "climate-neutral bloc"*** *with net-zero greenhouse gas emissions (NZE)*
- ***Electrification*** *is considered one of the key strategies to reach NZE goals*
- *Much of the NZE need will be met by shifting towards* ***electric transport*** *and* ***electrification of heating/cooling demand of buildings*** *using heat pumps*
- *In 2050,* ***electricity will become the dominant energy carrier for the buildings in EU.*** *The prognosed growth in demand by 2030 is 12% and 35% by 2050*



Share of electricity in total final energy consumption in the NZE scenario (2005-2030)

ENERGY WASTE IN BUILDINGS IS A GLOBAL PROBLEM

- ***Buildings*** *are responsible for approx.* ***40% of EU energy consumption, 50% of EU gas consumption,*** *and* ***36% of the energy-related CO_2 emissions. About 80%*** *of energy used in EU homes is for heating, cooling and hot water*
- ***85% of buildings in the EU were built before 2000*** *and* ***75% have poor energy performance****. 85–95% of today's buildings will still be in use in 2050*



DECARBONIZATION OF BUILDING STOCK IN EU

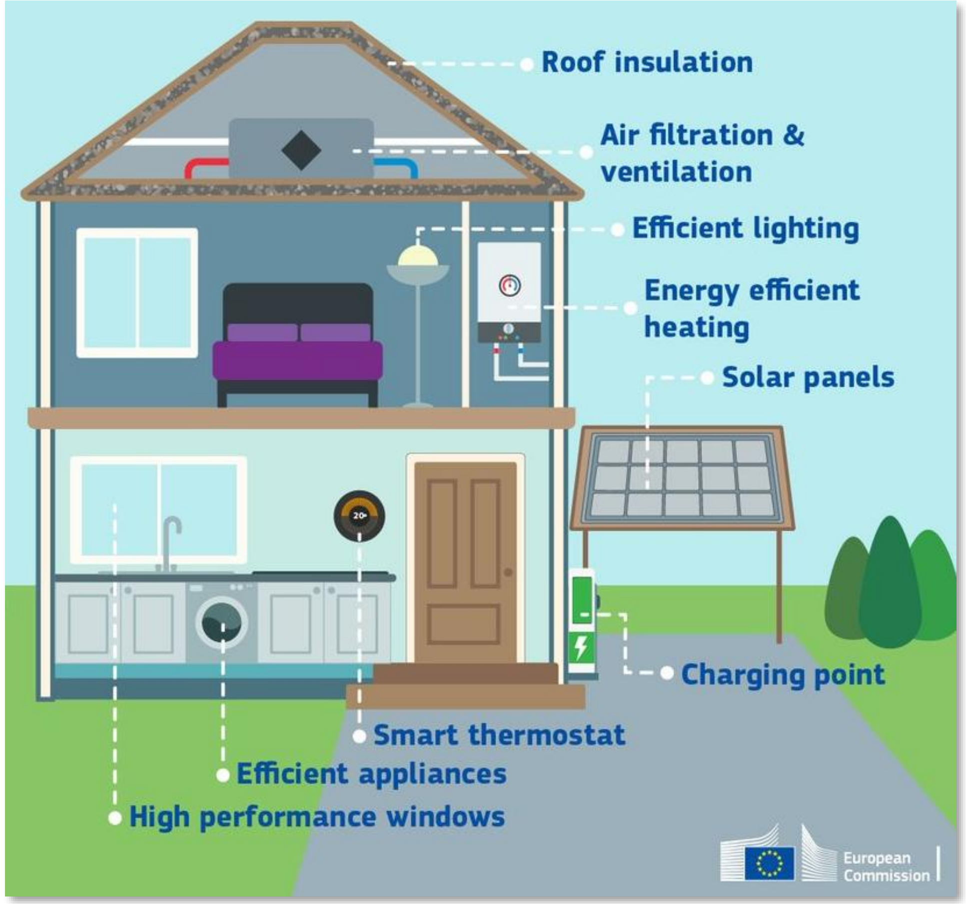
- *In 2002, the EU began implementing the* ***Energy Performance of Buildings Directive (EPBD)****, which is a framework to reduce energy consumption and boost decarbonization of buildings*
- *The EPBD requires all new buildings from 2021 to be* ***nearly zero-energy buildings (nZEB or class A),*** *i.e. must have a* ***high energy performance and very low energy needs****, covered largely by* ***onsite or nearby renewable energy sources***
- *From January 2030 the EPBD requires all new buildings to be* ***zero-emission buildings (ZEB, A+ or A_0), i.e. without on-site carbon emissions from fossil fuels***
- *EPBD demands the installation of* ***EV charging points*** *in new and significantly renovated non-residential buildings with more than 5 parking spaces, and in residential buildings with more than ten parking spaces*
- *EPBD introduces „Smart Readiness Indicator" to assess the technological readiness of the building to* ***interact with their occupants and adapt to signals from the grid (for ex., energy flexibility)***

EPBD

https://energy.ec.europa.eu

ZEB AND POWER ELECTRONICS

- *ZEB = HIGH ENERGY PERFORMANCE + LOCAL RENEWABLE ENERGY GENERATION + "ALL-ELECTRIC" LIFESTYLE*
- *ENERGY PERFORMANCE is the main feature of ZEB - PV installation (backed up with energy storage), heat pump, heat recovery ventilation, energy-efficient appliances and lighting, smart control of loads, energy arbitrage*
- *In result, ZEB consumes up to 4 times less energy than the traditional „old school" non-renovated building*
- *Most of the energy saving technologies used in ZEB are power electronics based*



Shutterstock

Image: Enphase

Image: SMA

Image: SMA

GOOD EXAMPLES OF BUILDING DECARBONIZATION

BAD EXAMPLES OF BUILDING DECARBONIZATION

https://greensunnj.com/solar-hall-of-shame/

BAPV vs BIPV- RENEWABLE ENERGY SHOULDN'T COME AT THE COST OF AESTHETICS !

Building-Attached Photovoltaics (BAPV)
lacks full integration into the building, adds additional load, with limited contributions to aesthetics and structural integrity

Building-Integrated Photovoltaics (BIPV)
is revolutionizing the solar industry by bridging the gap between electricity generation and building design


Image: Roofit Solar

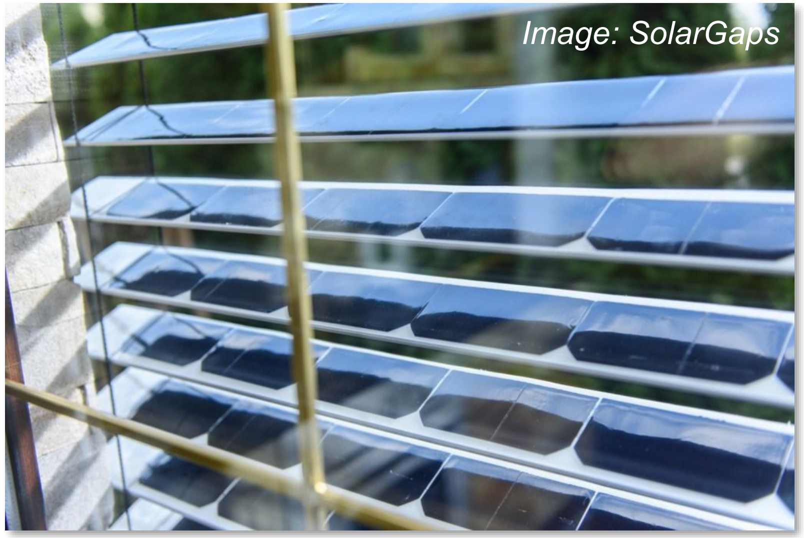

Image: Solarstone

THERE'S MORE OPTIONS THAN THE ROOFTOP PV!

SOLAR PV FENCES

SOLAR WINDOWS

SOLAR PANEL WINDOW BLINDS

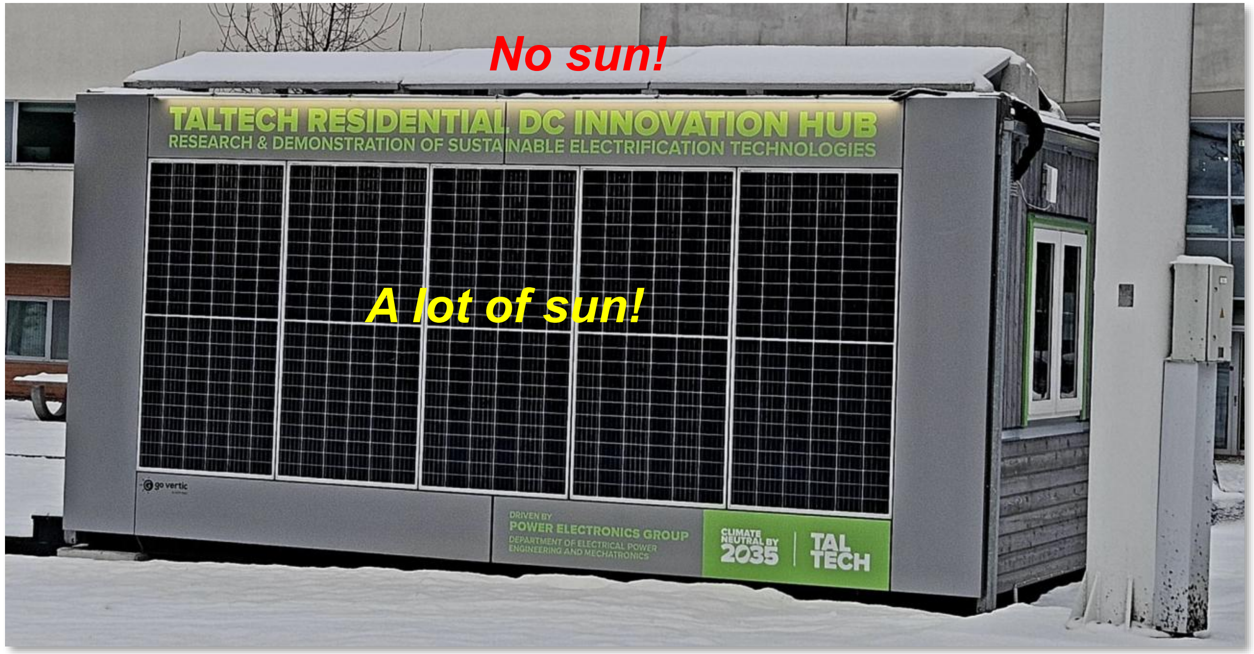


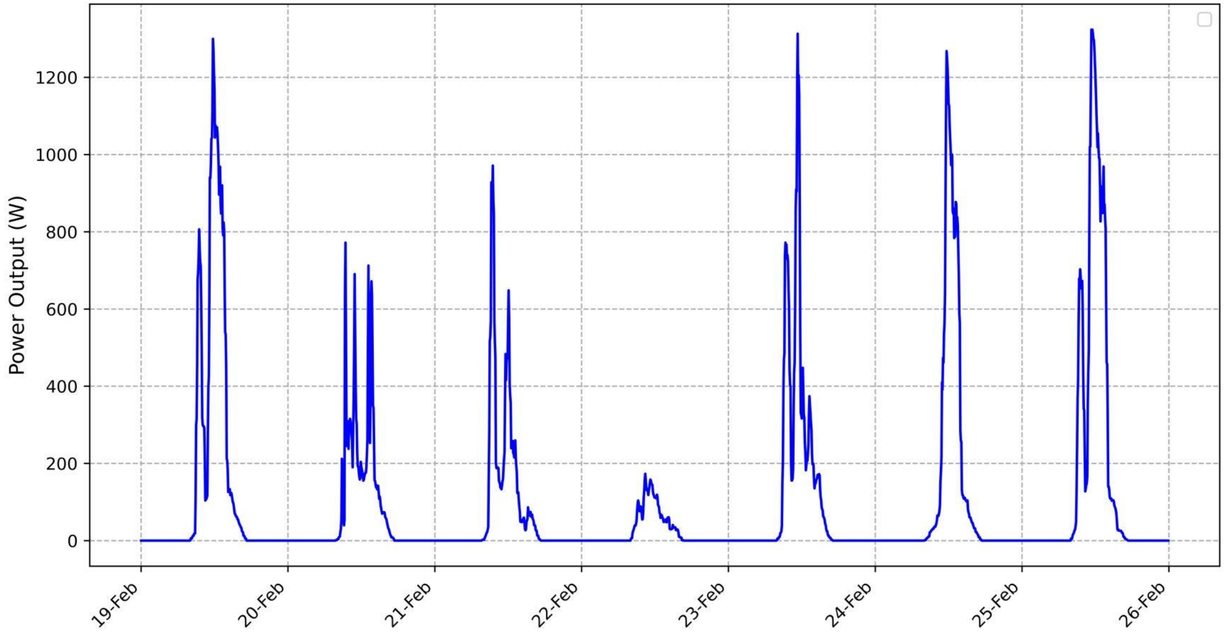
SOLAR BALCONIES

SOLAR FAÇADES

SOLAR FAÇADE – GENERATE WHEN OTHER DO NOT

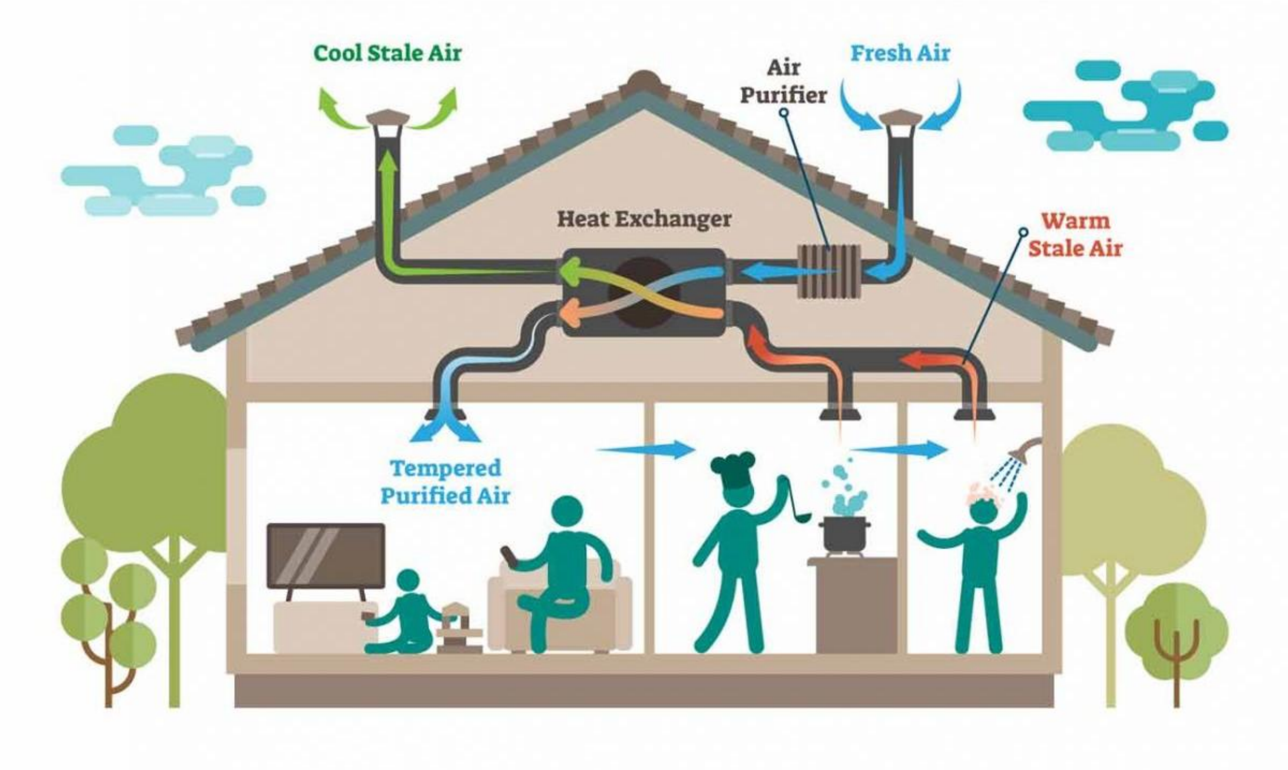
- **In Northern EU,** *snow covers the PV panels on the roof for long time, but they cannot generate much even without snow as sun ray's incident angle is highly unfavorable (sun rays nearly horizontal)*
- ***Solar façades*** *are never covered by snow, while sun incident angle is nearly ideal in winter*
- ***TalTech Residential DC Innovation Hub*** *has 5 PV modules of 144 half-cut cells rated for 360 W*
- *Test data from February 2026 show that the solar façade produced* ***17.9 kWh vs. 0 kWh*** *from the roof*





HEAT RECOVERY VENTILATION SYSTEMS

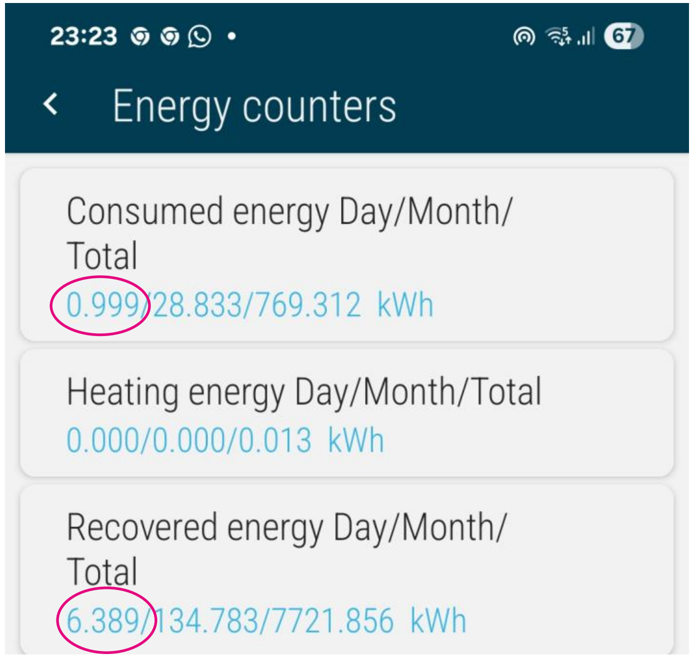
- ***Improved energy efficiency**: reduces heating demand of the buidling by **recovering up to 60–90% of the heat** from exhaust air; lowers energy bills*
- ***Better indoor air quality**: reduces buildup of carbon dioxide and radon levels, removes pollutants such as VOCs (from paints, furniture), allergens, and odors; maintains balanced indoor humidity levels.*
- ***Power electronics enabled smart control** and **easily pairing with PV** installation*



Temperature efficiency

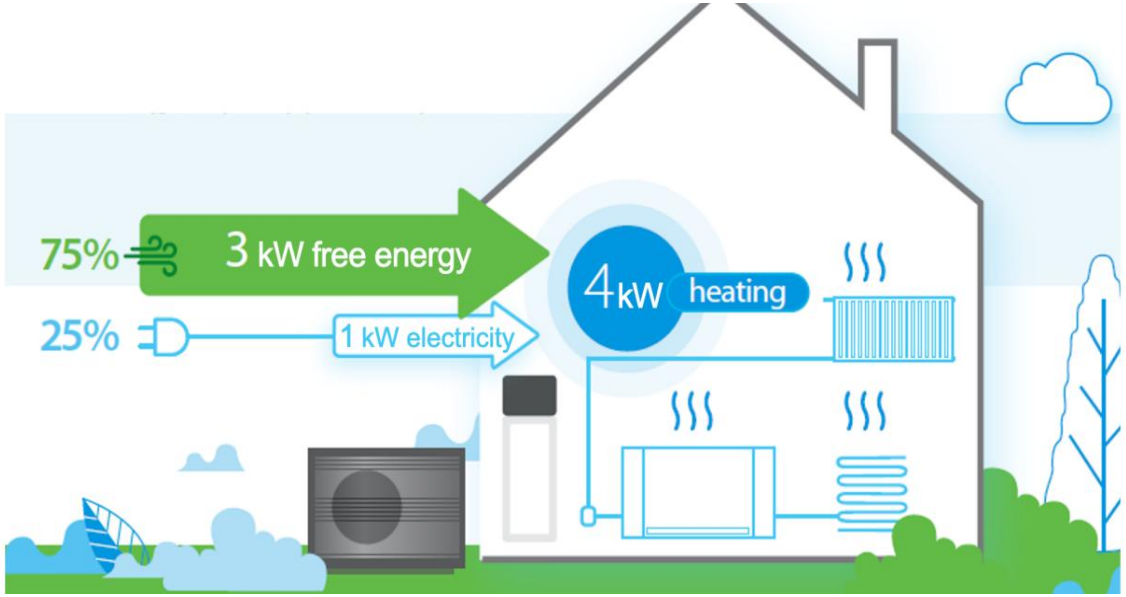
			Winter		
Outdoor temperature, °C	-23	-15	-10	-5	0
After heat exchanger, °C	15,6	16,7	17,4	18,1	18,9

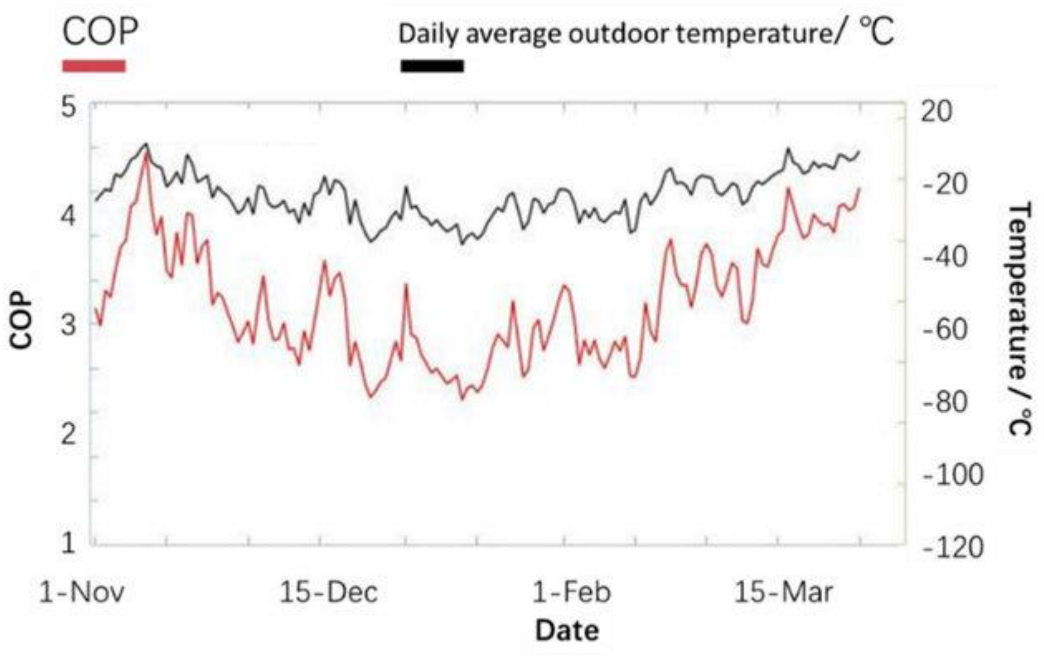
indoor +22 °C, 20 % RH



ELECTRIFICATION OF HEATING WITH HEAT PUMPS

- ***Excellent energy efficiency***: *can deliver up to 5 times more heat energy to a home than the electrical energy it consumes (see COP – Coefficient of Performance or SCOP – Seasonal Coefficient of Performance)*
- *Used for **space heating/cooling** and providing **domestic hot water** for showers and sinks*
- *Can be **easily paired with PV** installation*
- ***Power electronics enabled smart control** – heat pump can be operated as a **flexible and grid-responsive resource***

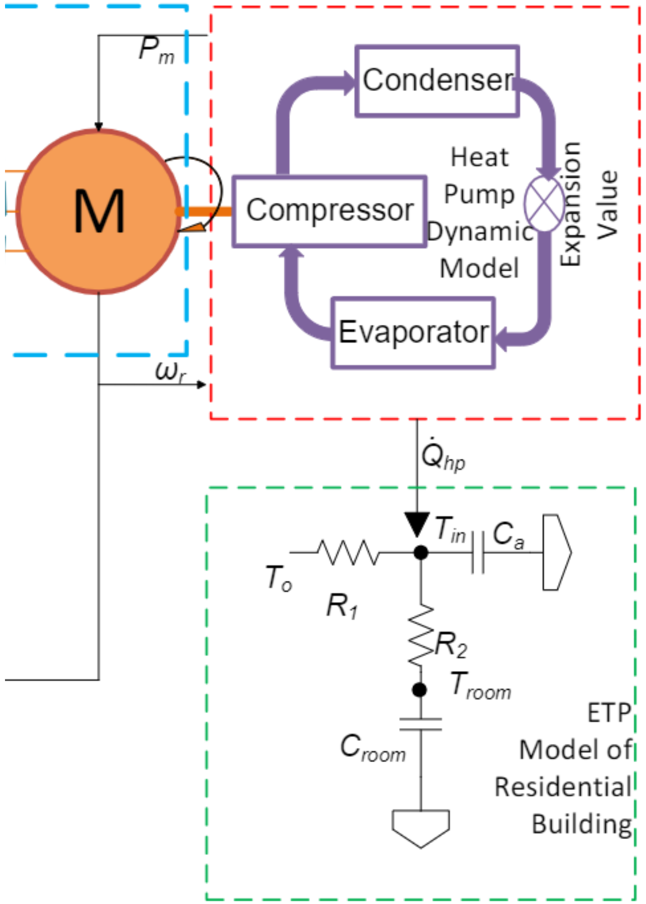




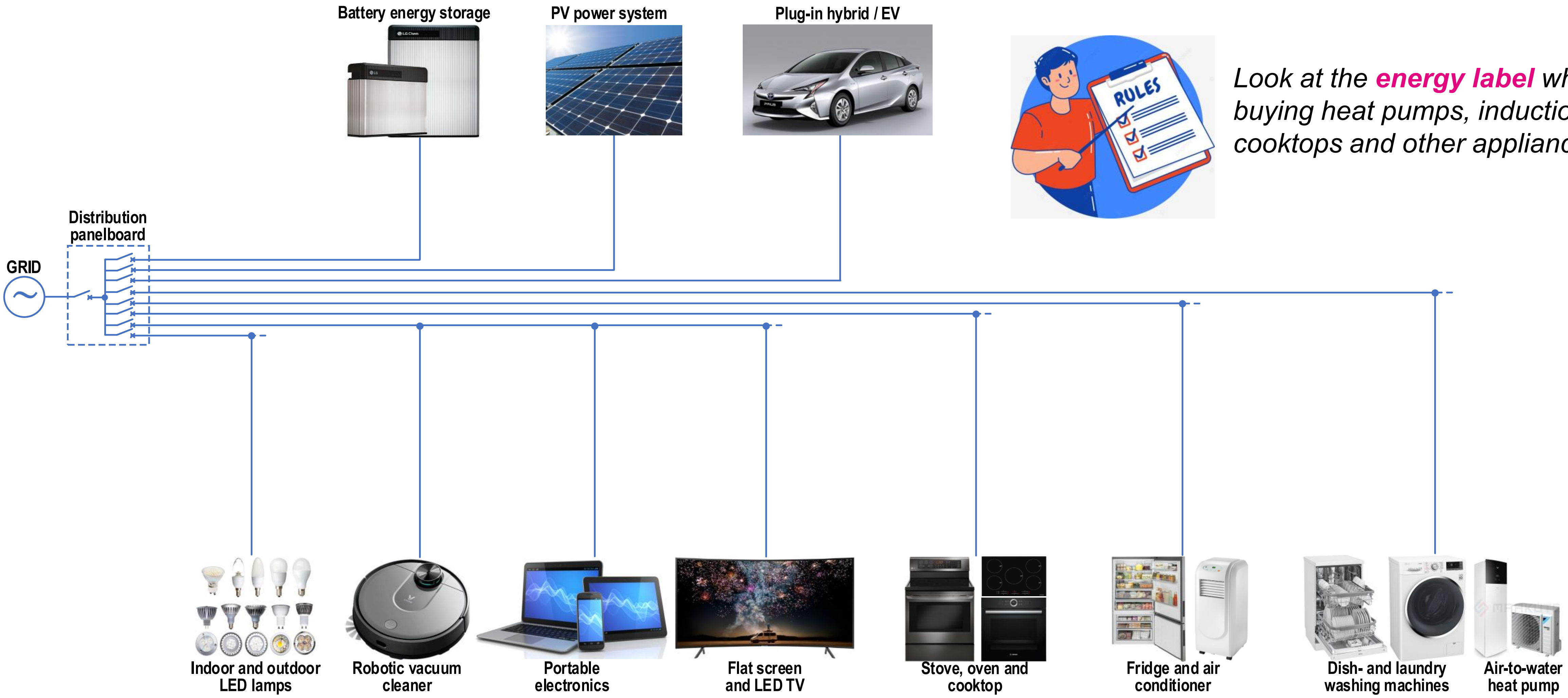
- Source: daikin.ie

HEAT PUMPS USE POWER ELECTRONICS

- Source: daikin.ie



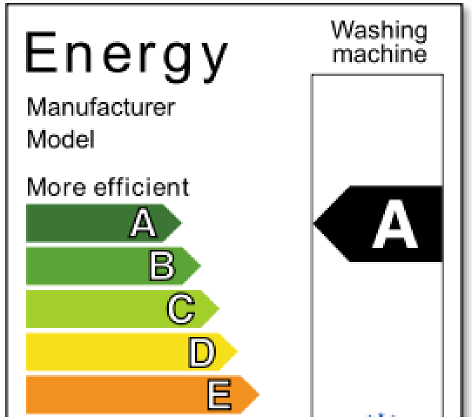
DECARBONIZATION OF BUILDINGS: „ALL-ELECTRIC“ LIFESTYLE WITH ZEB



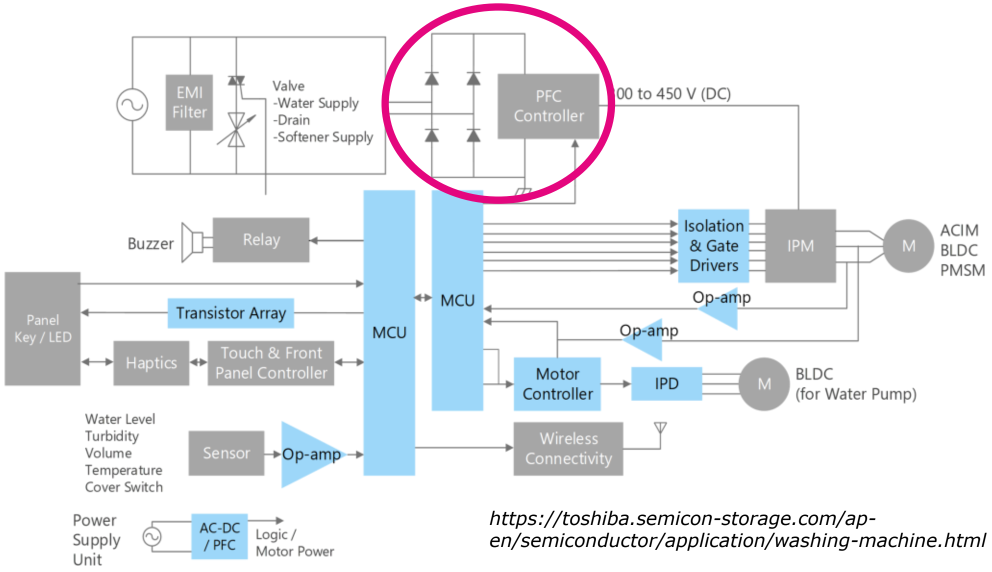
*Look at the **energy label** when buying heat pumps, induction cooktops and other appliances!*

CLASS-A ENERGY-EFFICIENT APPLIANCES

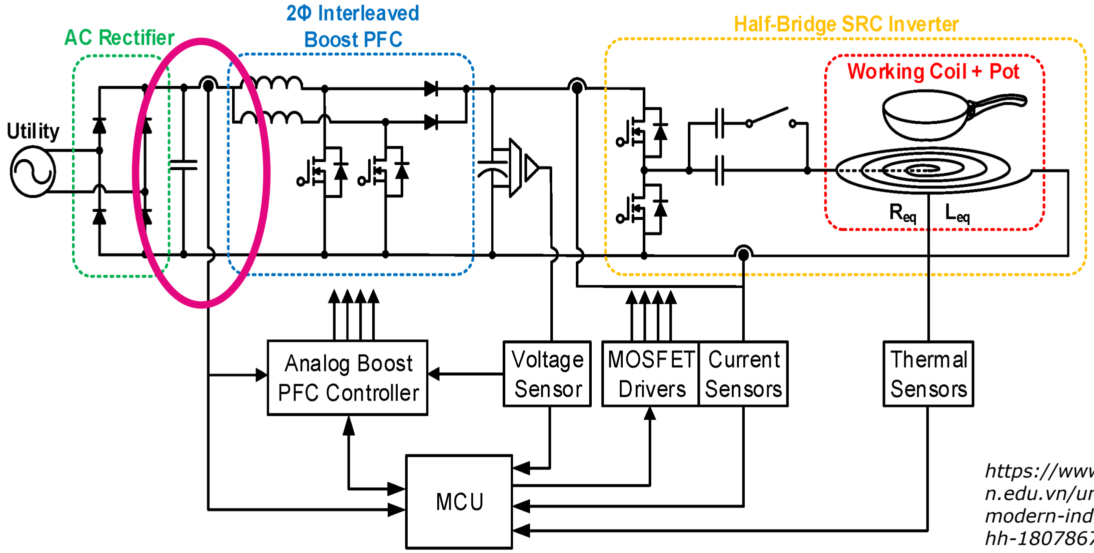
WASHING MACHINES, REFRIGERATORS, INDUCTION COOKTOPS, HEAT PUMPS, ETC.



THEY ALL USE DIRECT CURRENT (DC) FOR OPERATION !!!



https://toshiba.semicon-storage.com/ap-en/semiconductor/application/washing-machine.html

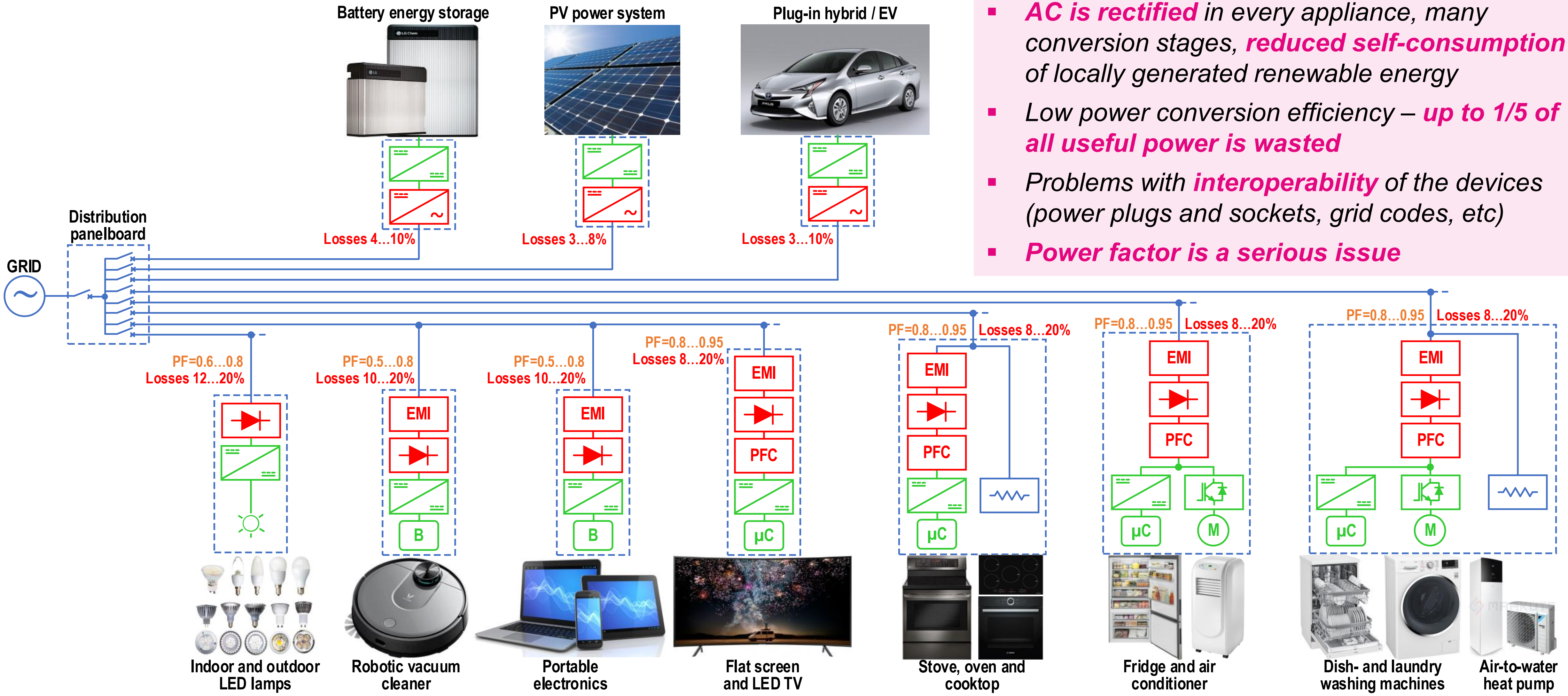


https://www.truongquoctesaigon.edu.vn/understanding-how-modern-induction-cooker-work-hh-18078675

AC-BASED ELECTRICAL SYSTEM OF A ZEB TODAY

WE ARE LIVING IN A DC WORLD WITHOUT FULLY REALIZING ITS TRUE POTENTIAL !

- ***AC is rectified*** *in every appliance, many conversion stages,* ***reduced self-consumption*** *of locally generated renewable energy*
- *Low power conversion efficiency –* ***up to 1/5 of all useful power is wasted***
- *Problems with* ***interoperability*** *of the devices (power plugs and sockets, grid codes, etc)*
- ***Power factor is a serious issue***

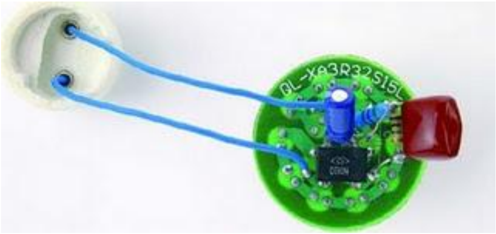


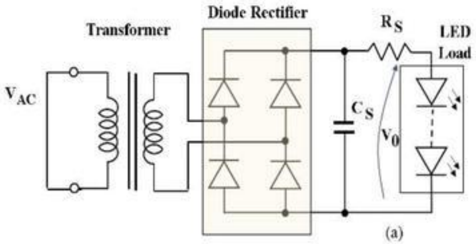
FULL-ELECTRIC LIFESTYLE WITH AC

A CLOSER LOOK AT THE POWER FACTOR ISSUE

PFC stage is required only above 75W - energy efficiency is additionally affected by the non-unity power factor

GU10 LED bulb (4.3 W)

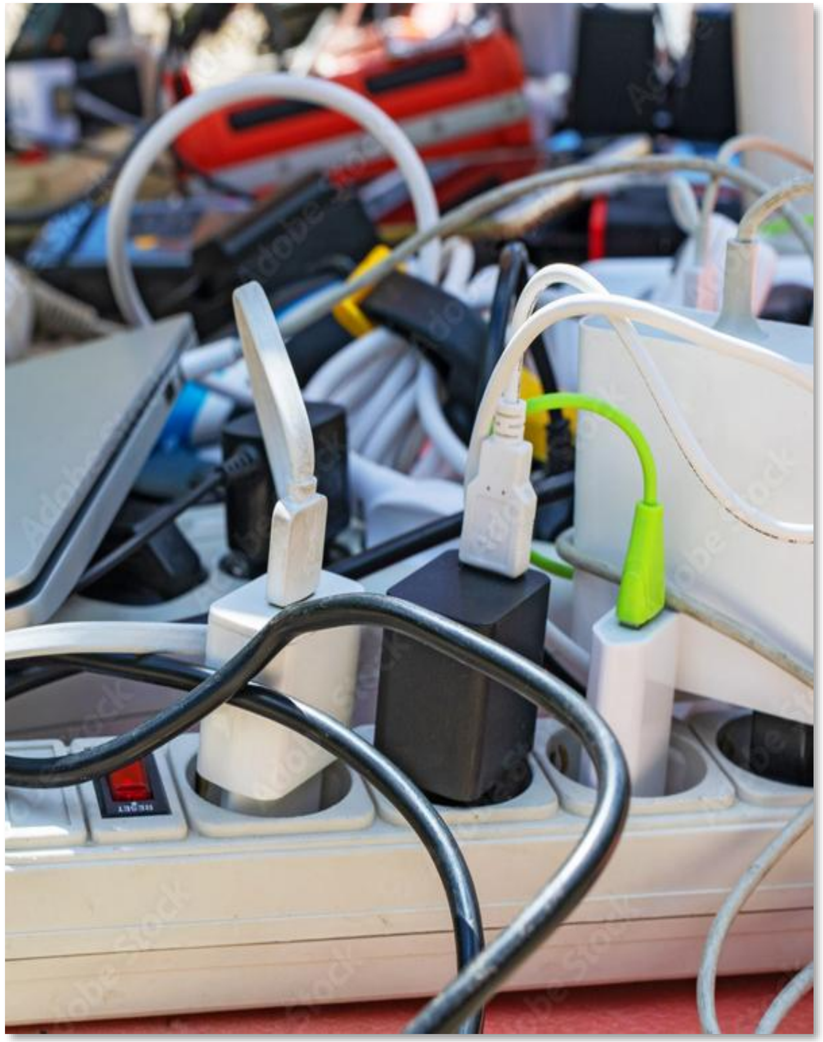




1	Urms	1	—	232.40	V
2	Irms	1	—	0.0337	A
3	P	1	—	4.33	W
4	S	1	—	7.83	VA
5	Q	1	—	6.52	var
6	Uthd	1	—	0.964	%
7	Ithd	1	—	74.420	%
8	PF	1	—	0.5534	

Laptop/Phone chargers (65 W)

No.	Function	Data	Units
1	Urms	232.37	V
2	Irms	0.5766	A
3	P	65.09	W
4	S	133.99	VA
5	Q	117.12	var
6	Uthd	1.122	%
7	Ithd	86.841	%
8	PF	0.4858	
9	Udc	19.243	V
10	Idc	-3.022	A
11	P	-58.16	W

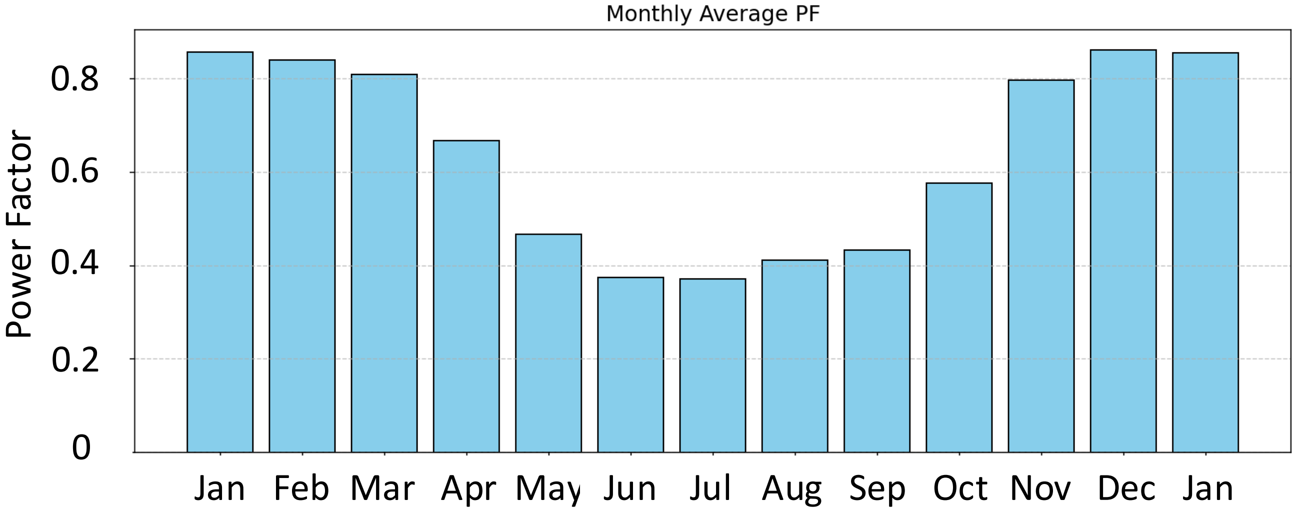


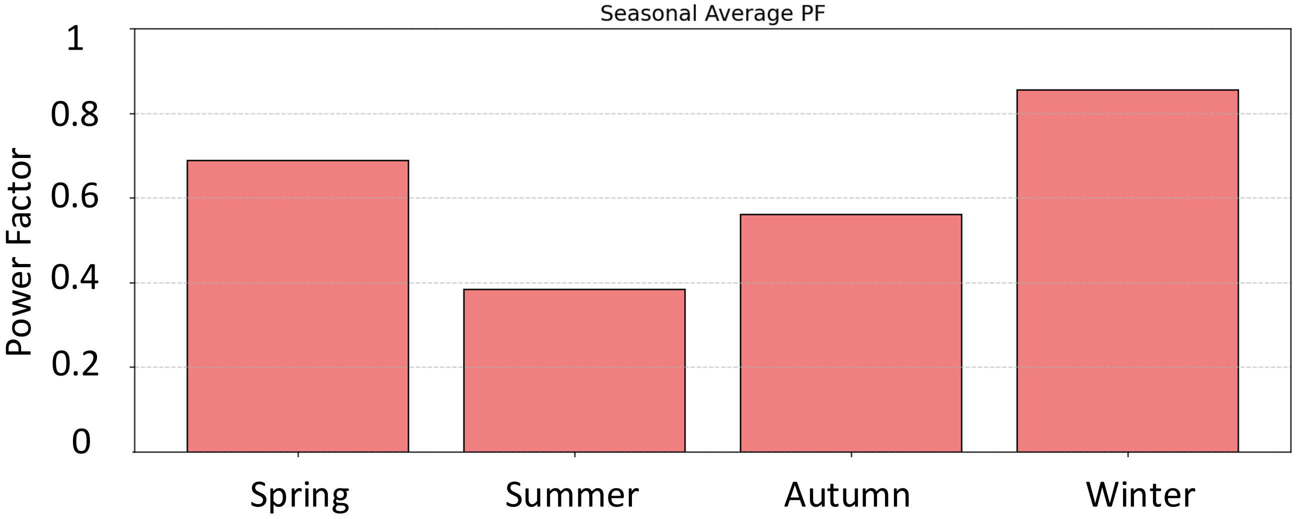
FULL-ELECTRIC LIFESTYLE WITH AC

A CLOSER LOOK AT THE POWER FACTOR ISSUE

176.7 m^2 single-family detached home

Location	*Estonia, Tallinn*
Total power of PV	*5 kWp*
Model of HP	*Thermia Atec HP 11*
Electric car	*BMW i3*
COP of HP	*COP 3.8 (+7/+45 °C)*
Habitants	*4*

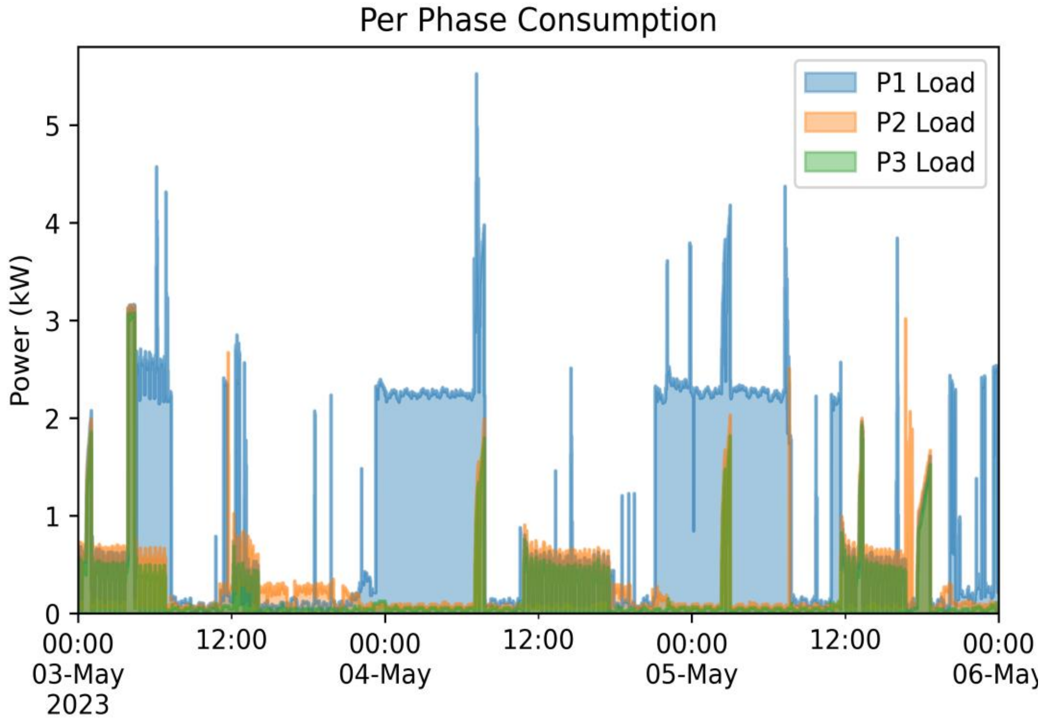


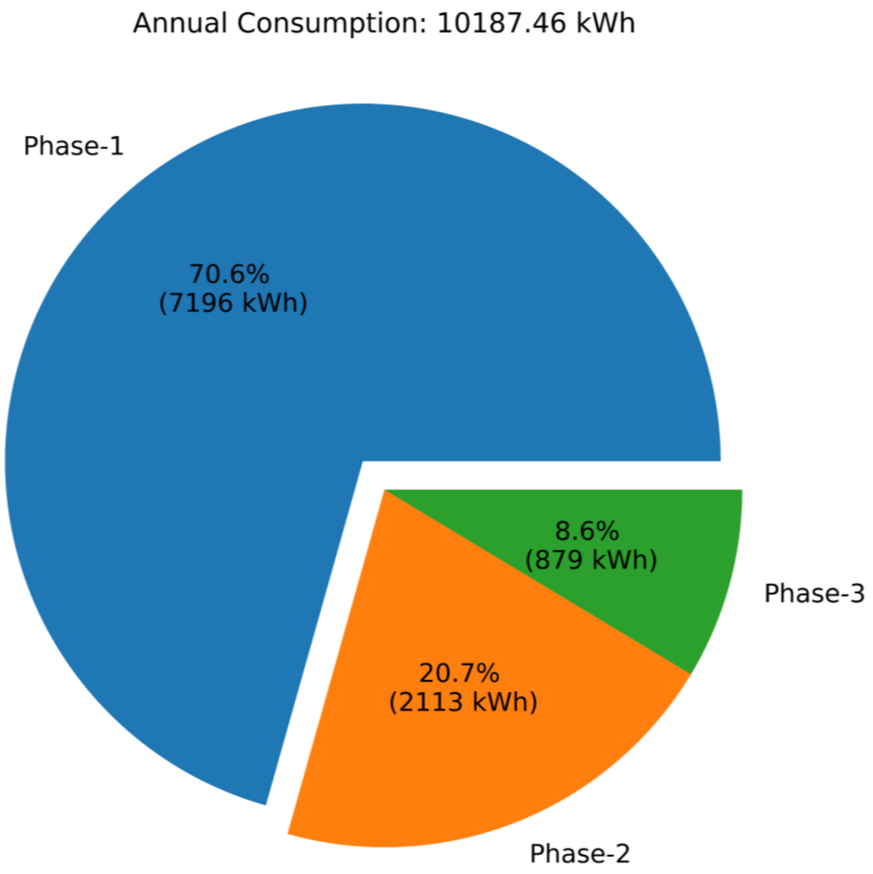


FULL-ELECTRIC LIFESTYLE WITH AC

A CLOSER LOOK AT THE PHASE LOAD IMBALANCE

Many residential (home) EV chargers have a single-phase grid connection with resulting negative impact on distribution transformers

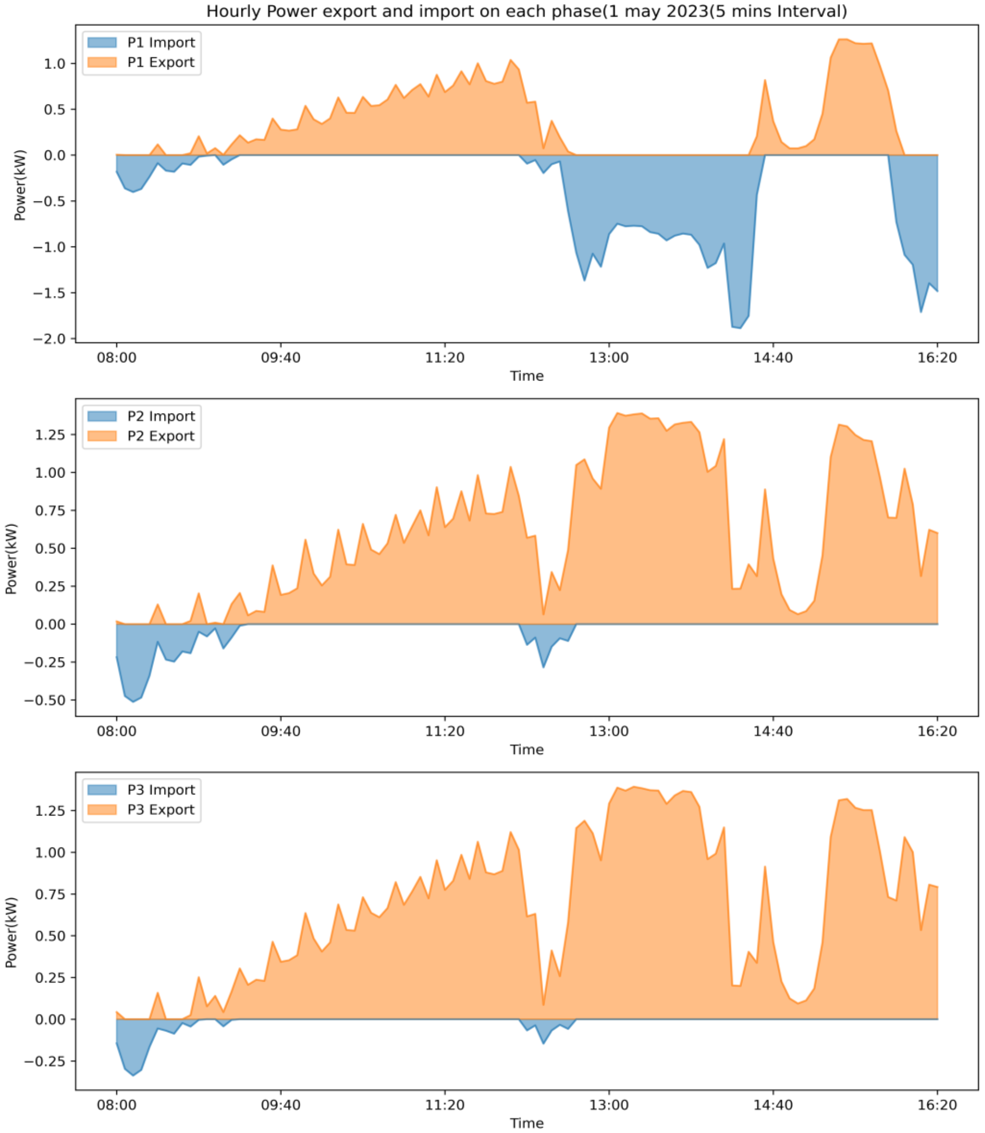


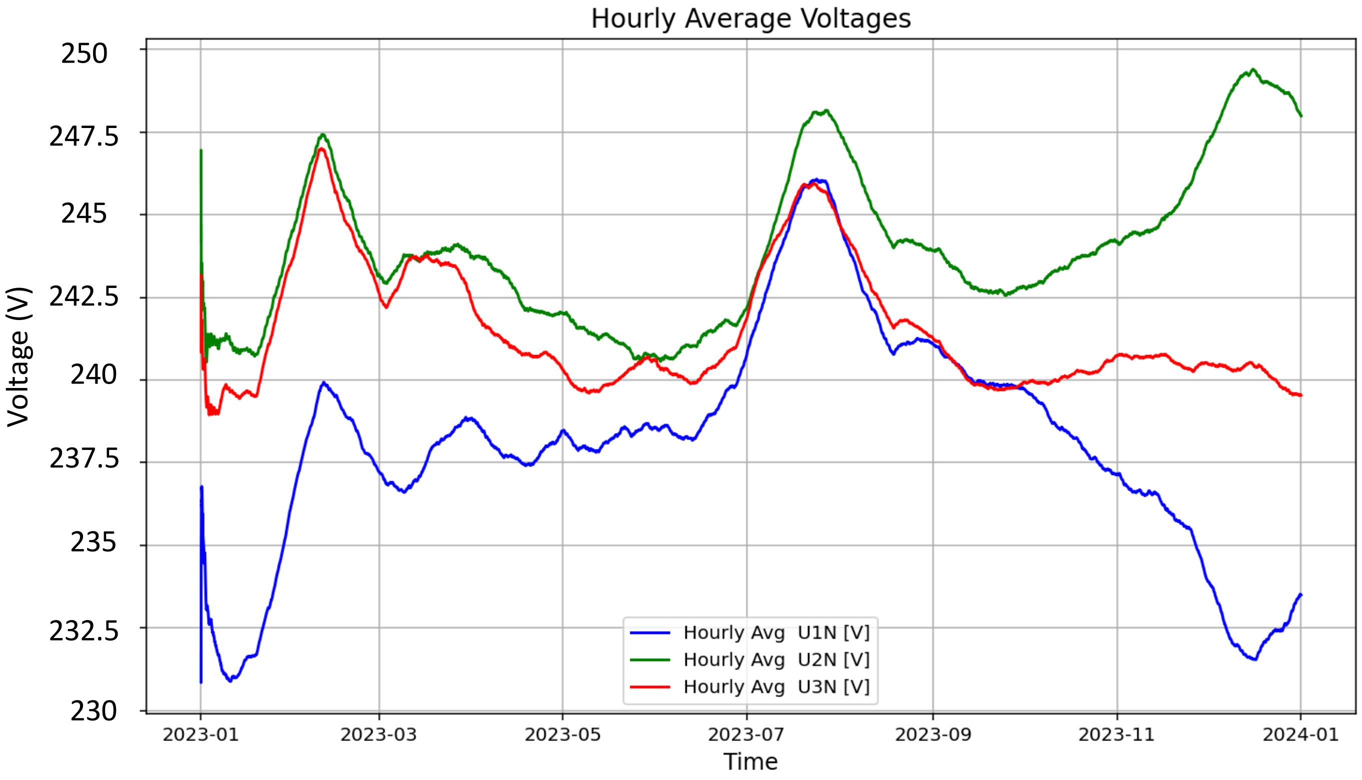


Hasan, S.; Blinov, A.; Chub, A.; Vinnikov, D. "PV Generation and Consumption Dataset of an Estonian Residential Dwelling", Dataset; DOI:10.48726/6hayh-x0h25 [Online]:https://data.taltech.ee/records/6hayh-x0h25

FULL-ELECTRIC LIFESTYLE WITH AC

ENERGY EXPORT/IMPORT BALANCE and VOLTAGE IMBALANCE ISSUES





Hasan, S.; Blinov, A.; Chub, A.; Vinnikov, D. "PV Generation and Consumption Dataset of an Estonian Residential Dwelling", Dataset; DOI:10.48726/6hayh-x0h25 [Online]:https://data.taltech.ee/records/6hayh-x0h25

FULL-ELECTRIC LIFESTYLE WITH AC

Electronic waste or e-waste

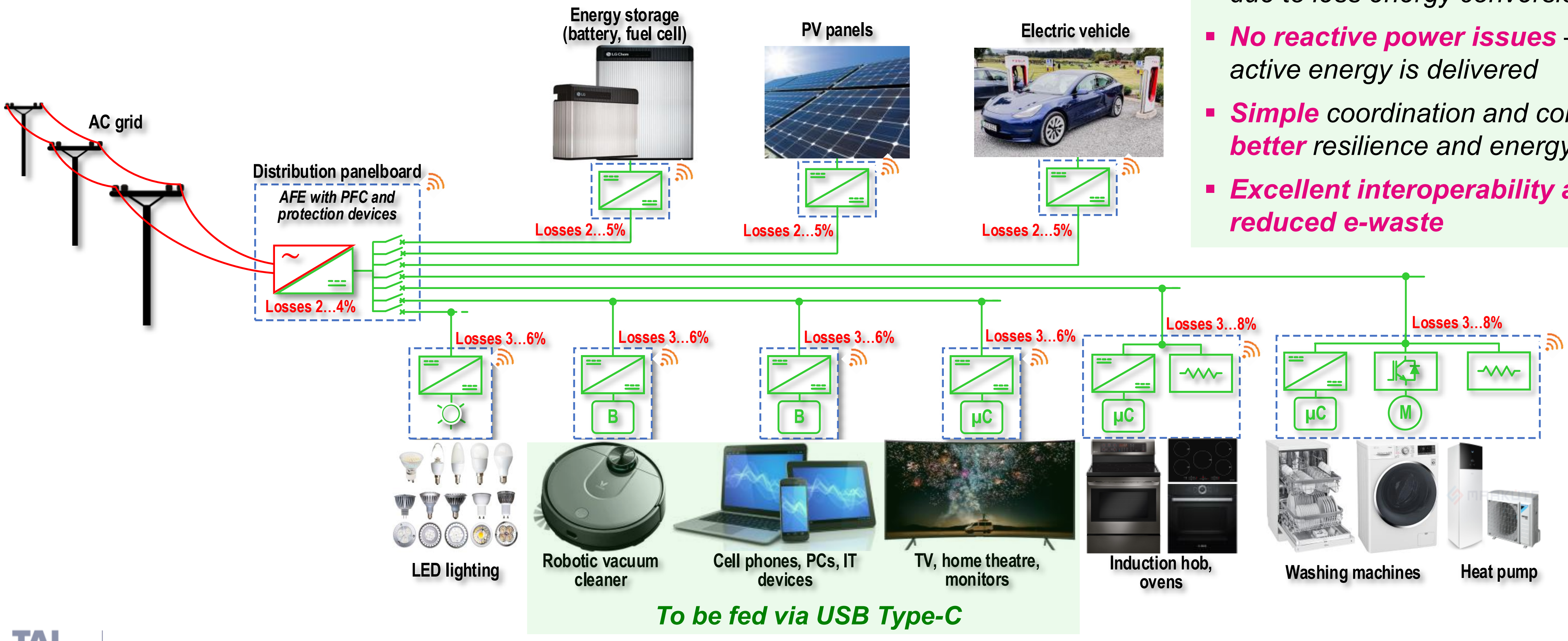
Is the fastest growing waste stream


Every problem has a solution😀😀

NEXT-GEN ELECTRICAL SYSTEM OF A ZEB

DC POWER DISTRIBUTION AND DC-FED APPLIANCES

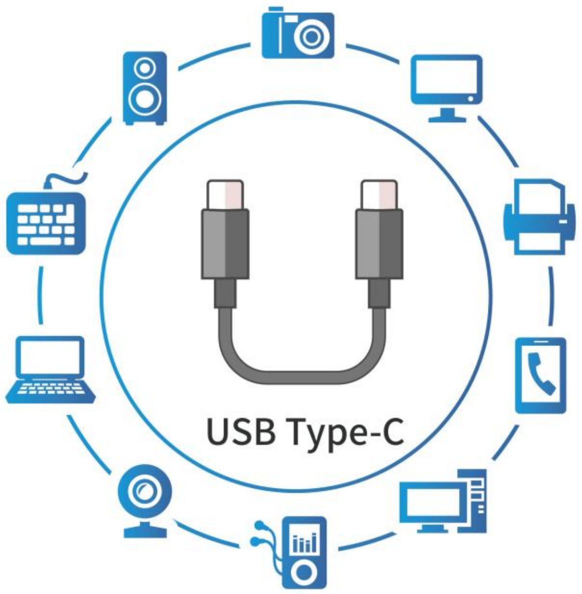
- ***Increased*** *efficiency and* ***maximized*** *self-consumption of renewable energy due to less energy conversion stages*
- ***No reactive power issues*** *– only active energy is delivered*
- ***Simple*** *coordination and control,* ***better*** *resilience and energy security*
- ***Excellent interoperability and reduced e-waste***

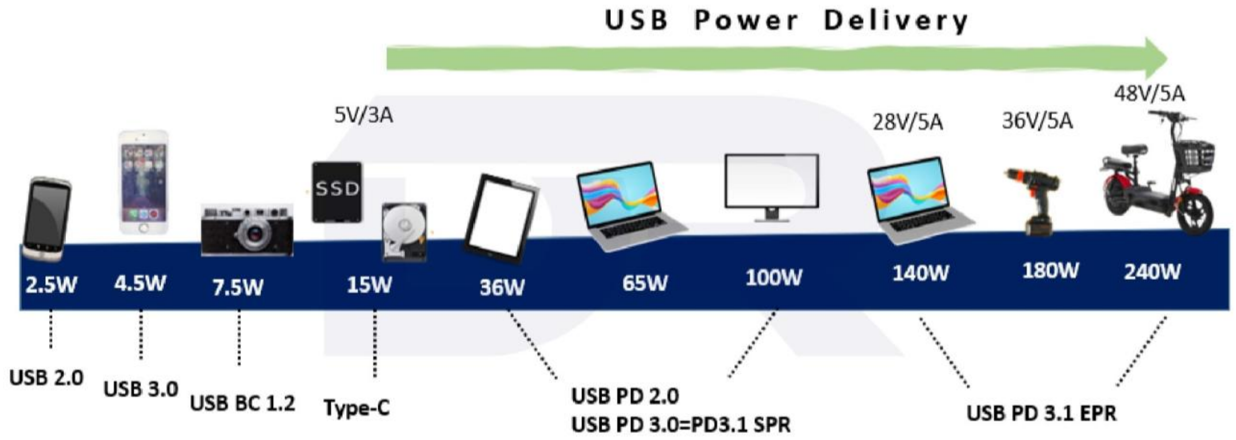


TAL TECH

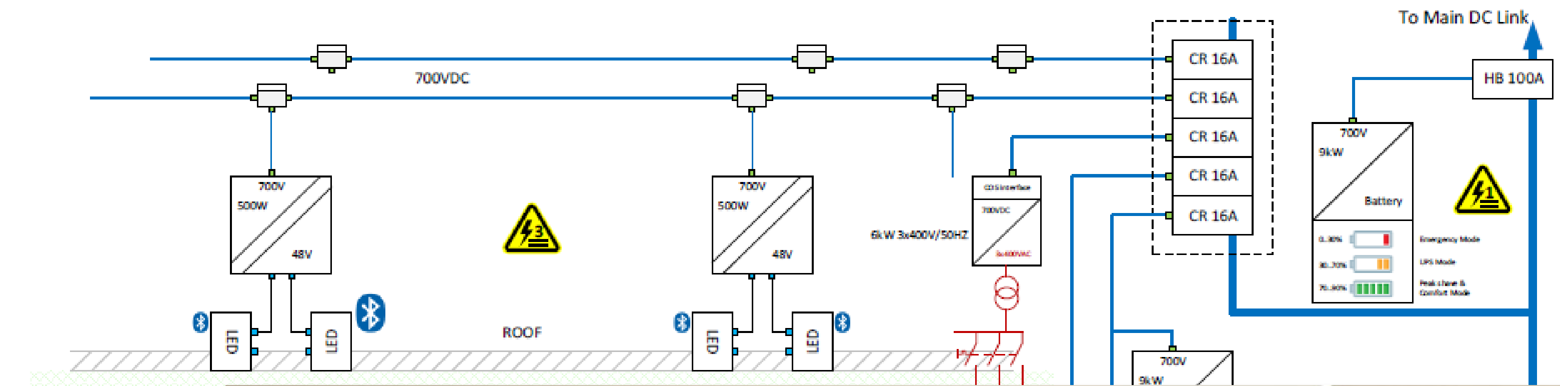
USB TYPE-C IS THE FIRST STEP TOWARD ENERGY-EFFICIENT AND INTEROPERABLE DC POWER DISTRIBUTION

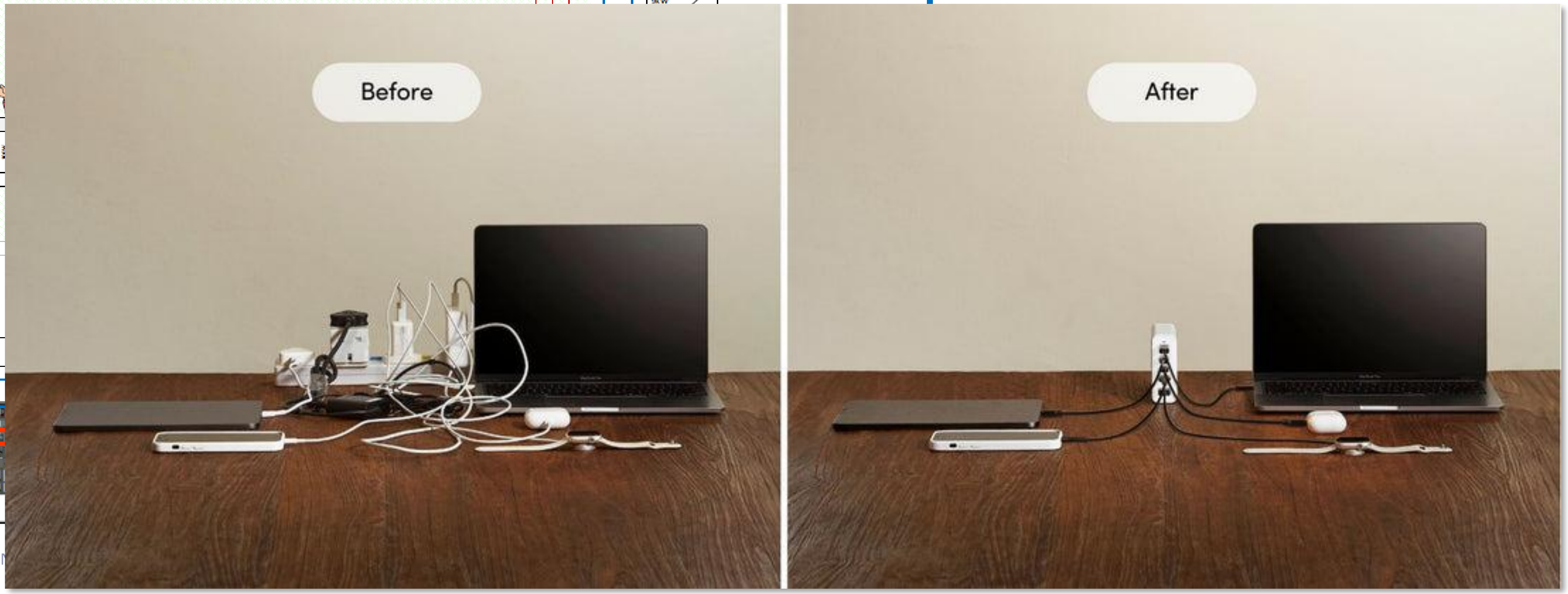
*Starting from 2025 the **USB Type-C became the common charging standard for small electronic devices in the EU**. Laptops will have to be equipped with a USB Type-C port by 28 April 2026.*





ENERGY NEUTRAL DC WORKSPACE





HISTORICAL CHOICE: FROM 230 VAC TO 350 VDC

- *The **LVDC** power distribution concept was proposed by **DC Systems** and implemented in Dutch standardization in **2018** (NPR9090 - Dutch Practical Guideline for the installations up to 1500 V DC)*
- *Starting **from 2021** the concept is continuously developed, improved and showcased by **Current/OS Foundation***
- ***350 VDC** is considered as a substitute for 230 VAC and **700 VDC** for 3x400 VAC******
- *Residential DC installations can be realized either with a **unipolar** or **bipolar architectures***
- ***Droop control** based power management, where voltage is used as a shared signal that reflects the power availability. The installation is **self-regulating** featuring excellent **resilience*****
- *Residential DC installations require ultrafast **solid-state circuit breakers (SSCB)** with tripping times less than **10 µs**. In combination with **residual current detection** and **arc fault mitigation** the SSCBs help eliminating safety concerns associated with DC and ensure **ultimate safety** of residents and property*

SYSTEMS by Schneider Electric

Current/OS

** https://currentos.org/technical-rules/*

*** Current/OS Distributed Electrical System: Droop Control Explained (https://www.youtube.com/@Current-OS)*

BENEFITS OF DC OVER AC IN HOUSEHOLDS*

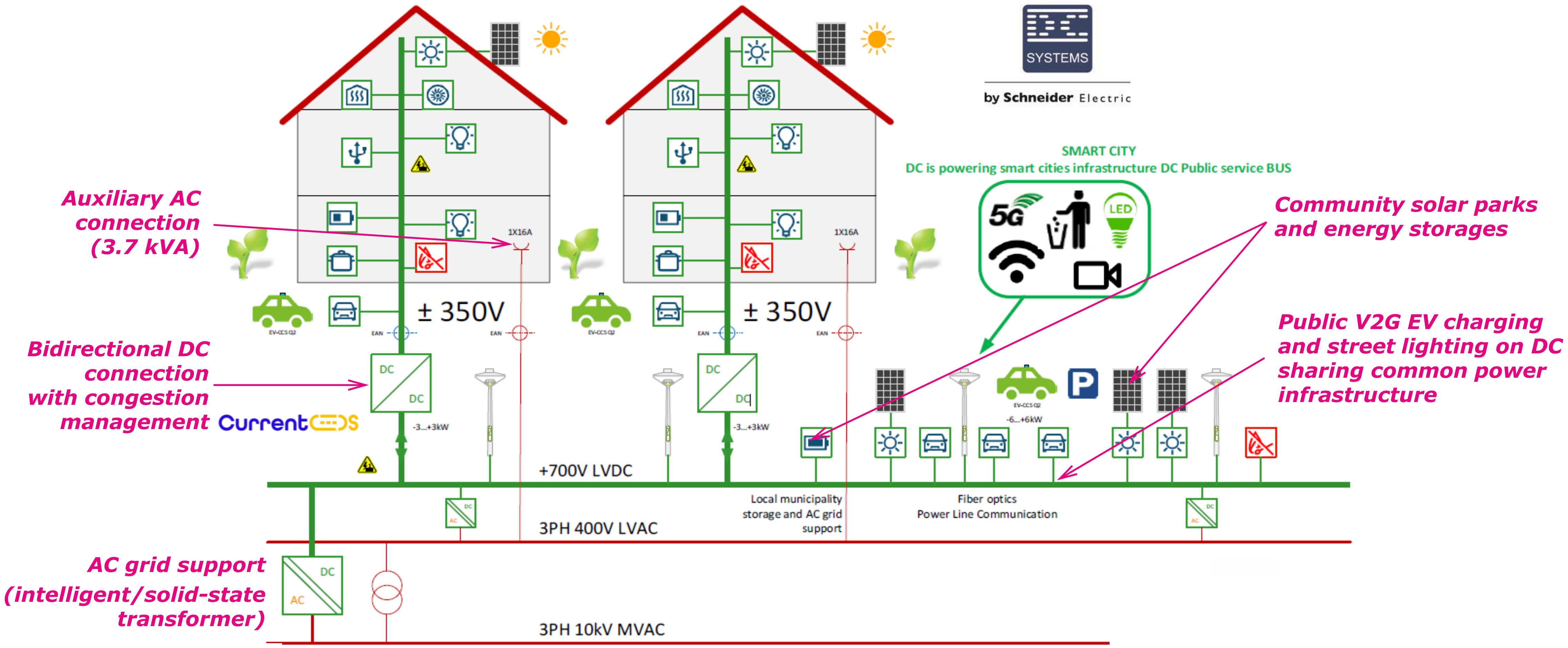
DC OPENS A NEW DIMENSION IN ENERGY PERFORMANCE OF BUILDINGS

- *100% power electronics enabled technology with ultimate control flexibility, efficiency, power density and reliability*
- *Up to 35% power loss reduction due to more efficient power conversion and distribution and better utilization of the local renewable energy (solar photovoltaics, battery energy storage and heat pump)*
- *Up to 55% reduction in distribution cabling mass (copper or aluminum)*
- *Up to 85% reduction in the required connection capacity to the AC distribution grid*
- *Up to 20% reduction in lifecycle costs when a building is fully converted to DC*
- *Easy implementation of Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G) technologies*
- *Resilient power supply during blackouts with possibility to support grid stability (power consumption curtailment, phase balancing, etc.)*

** EU Strategic Energy Technology Plan (implementation working group on DC technologies, subgroup on LVDC), September 12, 2024*

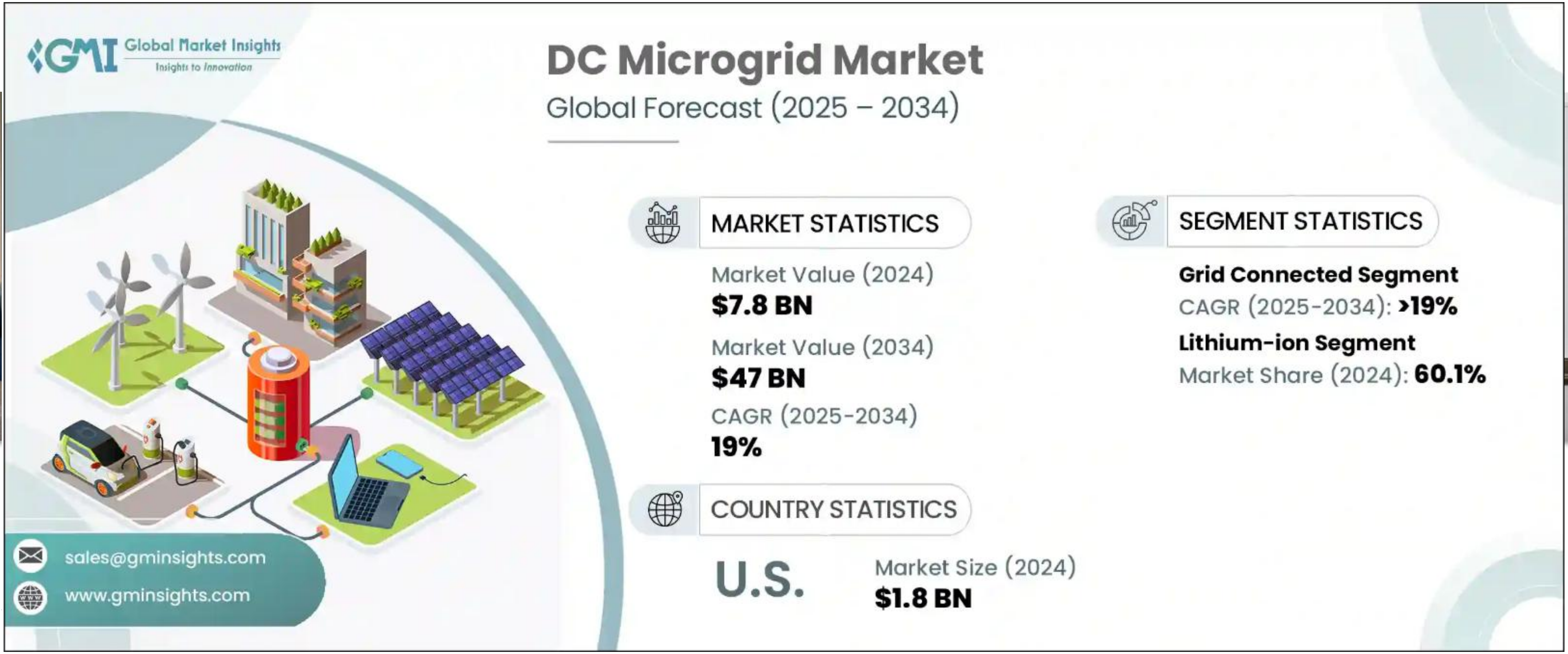
DC ELECTRIFICATION OF NEIGHBOURHOODS

***DC enables new revenue streams** for homeowners from participation in energy services and collective initiatives (EaaS, VPPaaS, energy communities, energy hubs, etc.)*



MAIN CHALLENGES OF DC TODAY

- *Lack of international standardization and certification schemes*
- *Lack of market-ready power electronic systems and appliances*
- *Lack of public awareness and technology demonstration*



IEC Standardization around DC

- Protection
- System & safety
- Devices

TC121
LV Switchgear
and control gear

TC64
Installation rules

TC34
Lightning

TC120
Electrical Energy
Storage (EES) System

TC17
HV switchgear
and control gear

TC69
Electrical power
energy transfer for
electrical vehicles

TC22
Power electronic systems
and equipment

TC82
Solar photovoltaic
energy systems

TC23
Electrical accessories
(Home and distribution)

TC8
System aspects of
electrical supply
(Grid connection)

TC57
Power System
management

TC13
Energy measurement &
control

SyC LVDC
Low voltage DC

The picture can't be displayed.

CurrentOS

Defining Standards for DC Microgrids

- **Global DC partnership**
- **Member of IEC SyC LVDC**
- **100+ partners** to date, more joining every month
- **25 countries represented in**
  - North America
  - Europe
  - Asia
- **Universities join for free**
- **https://currentos.org**

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AE Conversion, Aimbridge Energy, ALENCON, ambibox, AmpereXt, ARRIBA TECH, Basil, CARLO GAVAZZI, Cascara Energy, CHARGERLY, CITYTEC, claros, COMSYS, DAIKIN, DC GRID, DC Expert, DCpportunities, DCPlusEnergiehaus, DANISENSE, SYSTEMS by Schneider Electric, Design with DC, DEP Direct Energy Partners, dynniq energy, EDF, Elektro Internationaal, enteligent, epic power, EQUANS, Fuji Electric, ferroamp, GenCell, hager, Hisense, MICROSENS, INNOVENTUM, Jacobs, KelTech IoE The Net Zero Network, KONE, LEM, MEAN WELL, microgrid solutions, MR, Nexans Electrify the Future, oe, OMNIPOWER, POSETRON, NKT, prysmian, Quooker, RAMBOLL, SATEC, SIEMENS, socomec, staqx, Southwire, tecnalia, TRANE TECHNOLOGIES, VINCI ENERGIES, VOLSTORA, vyomaa energy, VOLTSERVER Digital Electricity, Watt&Well Converting Power into Confidence, Winline Technology, WORLD4SOLAR, ZIGN innovations

Universities

inesc id lisboa, JUNIA Grande école d'ingénieurs, Northeastern University, POLITECNICO MILANO 1863, RWTH AACHEN UNIVERSITY, TAL TECH, TU Delft, Technische Universität Ilmenau, Technical University Sofia, UNINOVA, UR Université de La Réunion, UEX, University of Strathclyde Glasgow, Universität Stuttgart, Xi'an Jiaotong University

Certification

DAMSTRA LAB Electrical Power Testing, DEKRA, INESCTEC, intertek Total Quality. Assured., NMi

Trade Goups

BSRIA, DG4SC, EMerge Alliance, europacable, GIMELEC, VOLTA, Stichting Gelijkspanning Nederland

ODCA
direct current by zvei

Open Direct Current Alliance ODCA

International non-profit organization

- With **80+** members
- In **16** countries
- On **3** continents

What do we do

- Publish system reference document
- Networking
- Knowledge exchange
- Best practice sharing
- Contribute to IEC & UL standardization

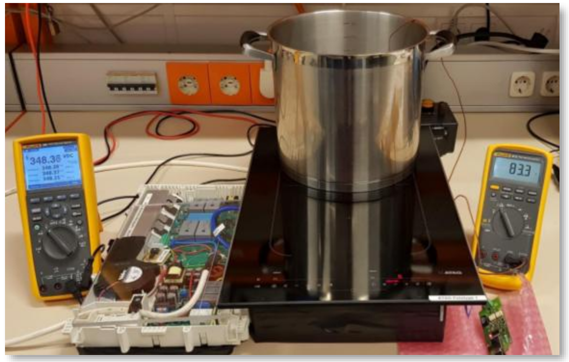
https://odca.zvei.org/

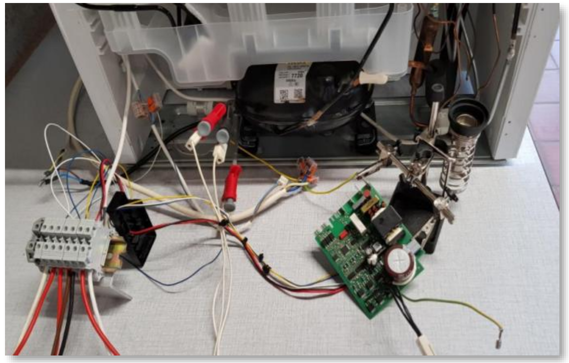
350 VDC TECHNOLOGY IS VERY FAST DEVELOPING

RECENTLY IS A TECHNOLOGY VALIDATION AND DEMONSTRATION PHASE (2020-2027)

- *Big players (Schneider Electric, EATON, ABB, etc.) strongly support the technology development and innovation*
- *Solid state circuit breakers (DC Systems B.V., Blixt, DC Opportunities B.V.)*
- *USB-C PD (power delivery) 100 W wall socket outlet (DC Systems B.V.)*
- *Public light LED drivers (DC Systems B.V., Tridonic)*
- *Induction cooktop (ATAG Benelux)*
- *Hood fan (ATAG Benelux)*
- *Refrigerator (ATAG Benelux)*
- *Heat pumps (NRGtec)*
- *Under development: coffee machine, oven, microwave, washing machines, etc.*

SYSTEMS ATAG BENELUX DCpportunities BL!XT
TRIDONIC ferroamp




https://gelijkspanning.org/
https://www.dc.systems/
https://blixt.tech//

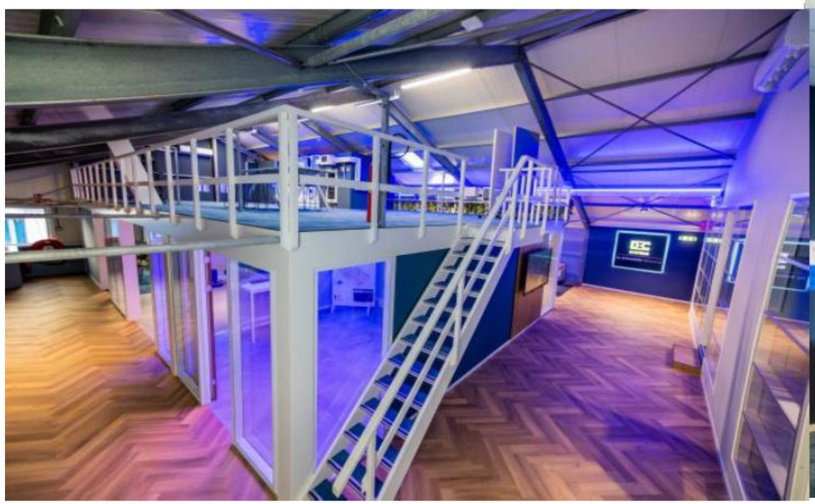
DC TECHNOLOGY DEMONSTRATION FACILITIES (1)

DIRECT CURRENT EXPERIENCE CENTER (AALSMEER, NL)

DC SYSTEMS

by Schneider Electric

- DC-powered office setups;
- Energy recovering industrial automation equipment,
- Solar technology;
- EV charging and more.



Book your visit via email: experience.center@dc.systems

DC TECHNOLOGY DEMONSTRATION FACILITIES (2)

GREEN VILLAGE, TU DELFT (NL)

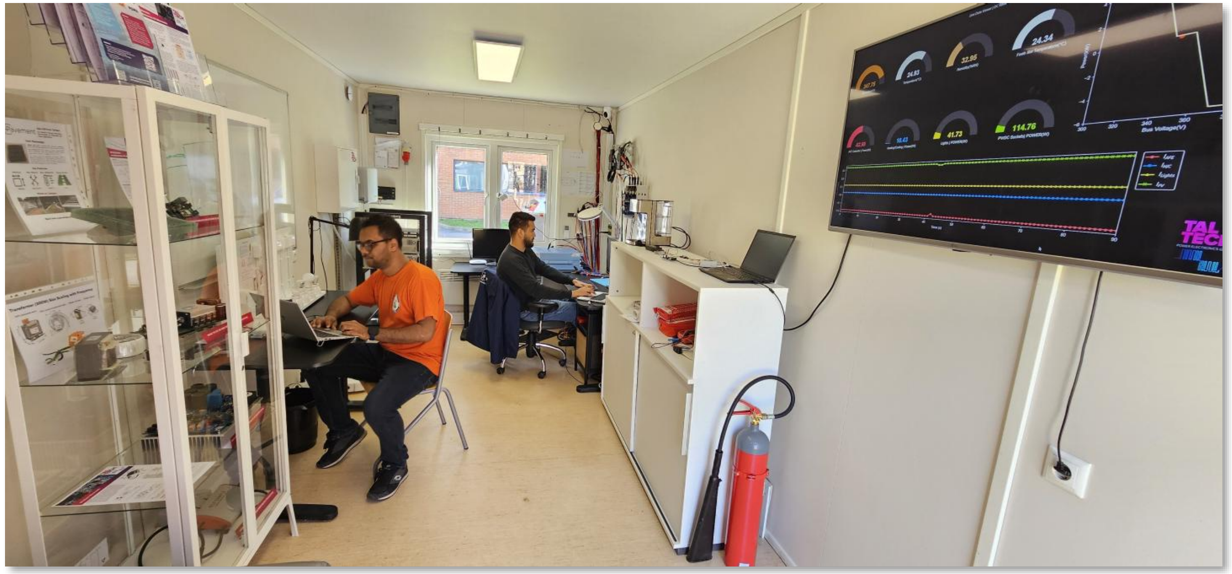
DCopportunities

https://dc-opportunities.com/dcmicrogrids/meshed-350-700v-dc-microgrid-at-the-green-village/

DC TECHNOLOGY DEMONSTRATION FACILITIES (3)

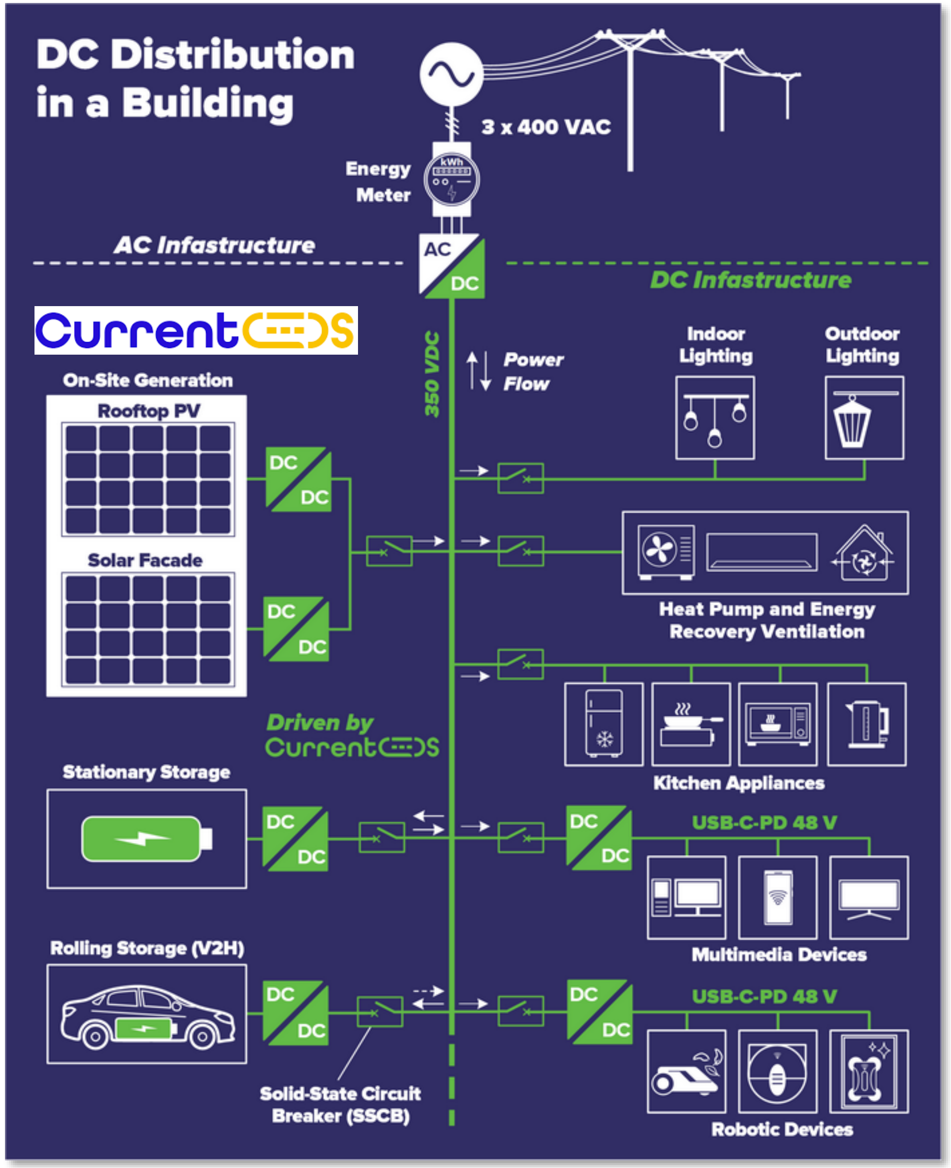
TALTECH RESIDENTIAL DC INNOVATION HUB (TALLINN, ESTONIA)

- *The first DC experience center in the Northern Europe*
- *The first academic member of Current OS Foundation*
- *International open platform for research and demonstration of residential DC power distribution technologies*
- *Validation of the net-zero-energy solutions (workplace, space heating and cooling, ventilation, etc.)*
- *Living lab allows for blending the everyday real-life experience of pilot users with academic research*
- *Data collection for the future design of the energy-neutral homes*
- *Book your visit via email at: i3dc@taltech.ee*

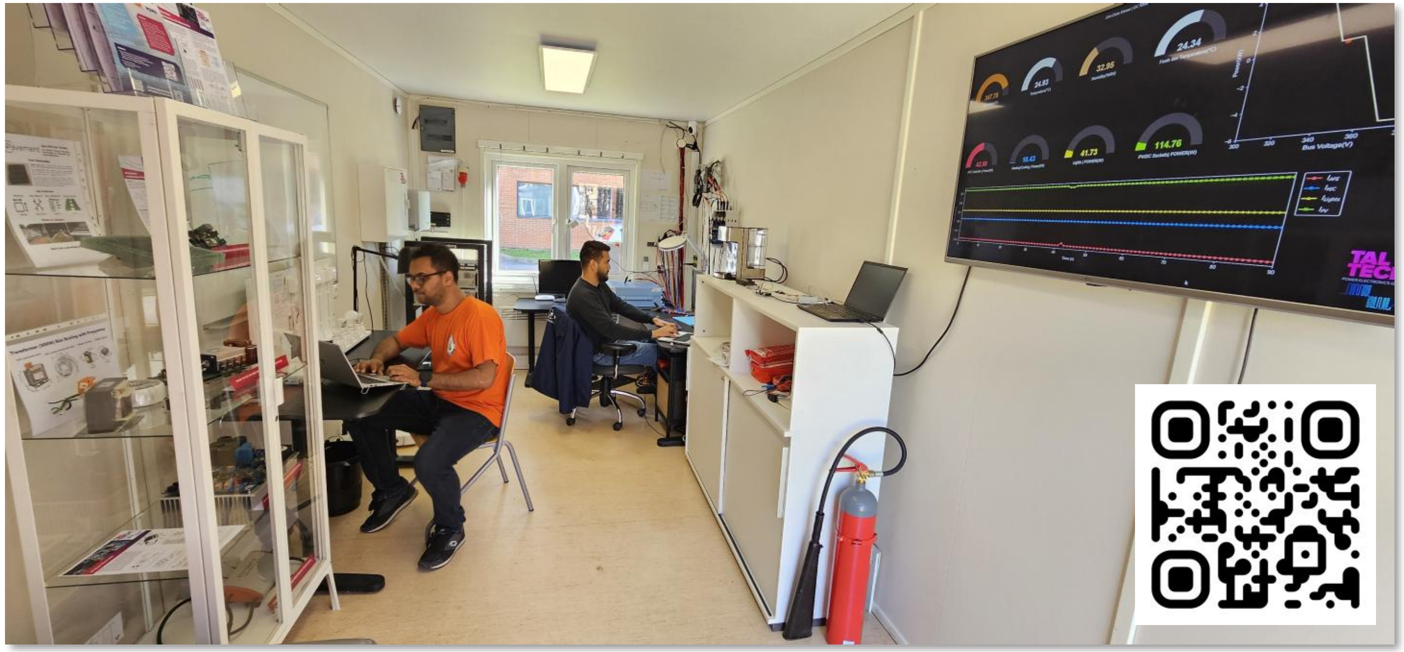


TALTECH RESIDENTIAL DC INNOVATION HUB

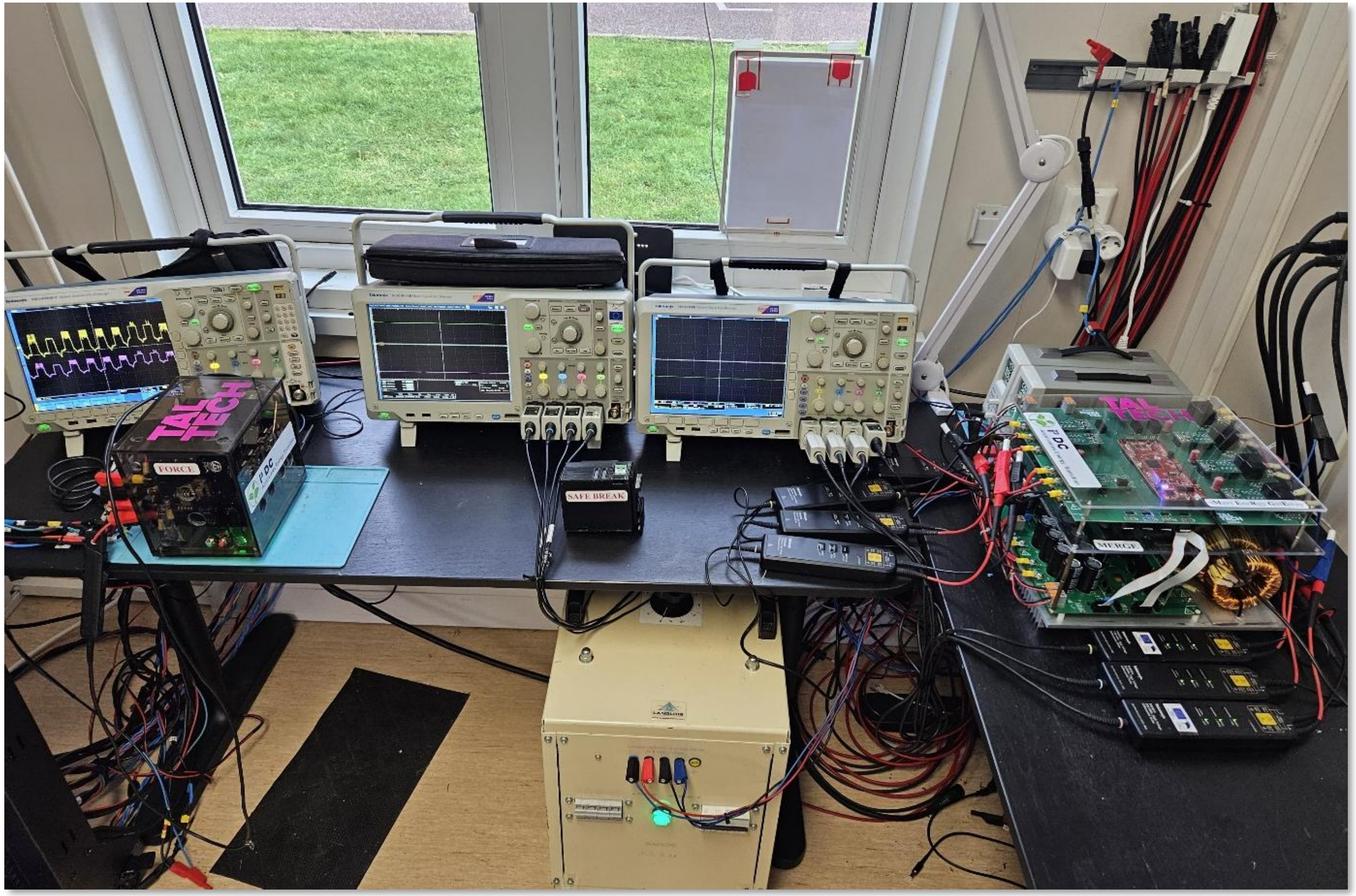
THE FIRST DC EXPERIENCE CENTER IN NORTHERN EUROPE



- *Thermally insulated for year-round operation*
- *2 energy-neutral working places for researchers*
- *350V±30V DC droop-controlled microgrid (operating system Current/OS)*
- *Solar facade composed of 5 c-Si PV modules*
- *Solar roof with 3 south-facing and 3 north-facing c-Si PV modules*
- *Battery energy storage*
- *LED lighting and heat pump fed from DC (both are energy neutral)*
- *Solid-state protection (both commercial and research samples)*
- *DC appliances (continuous development)*
- *Data logging and visualization*



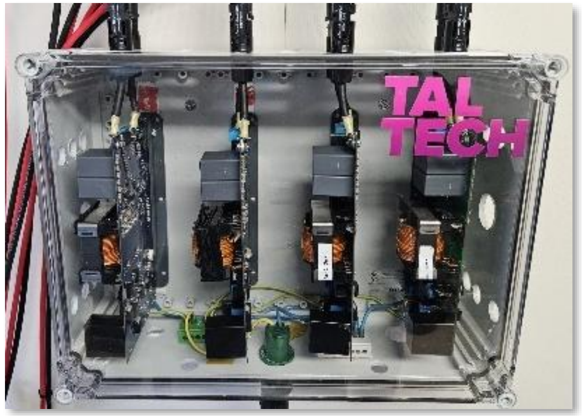
TECHNOLOGIES UNDER TEST IN DC INNOHUB



SAFEBREAK

MERGE

FORCE



FlexiVerter

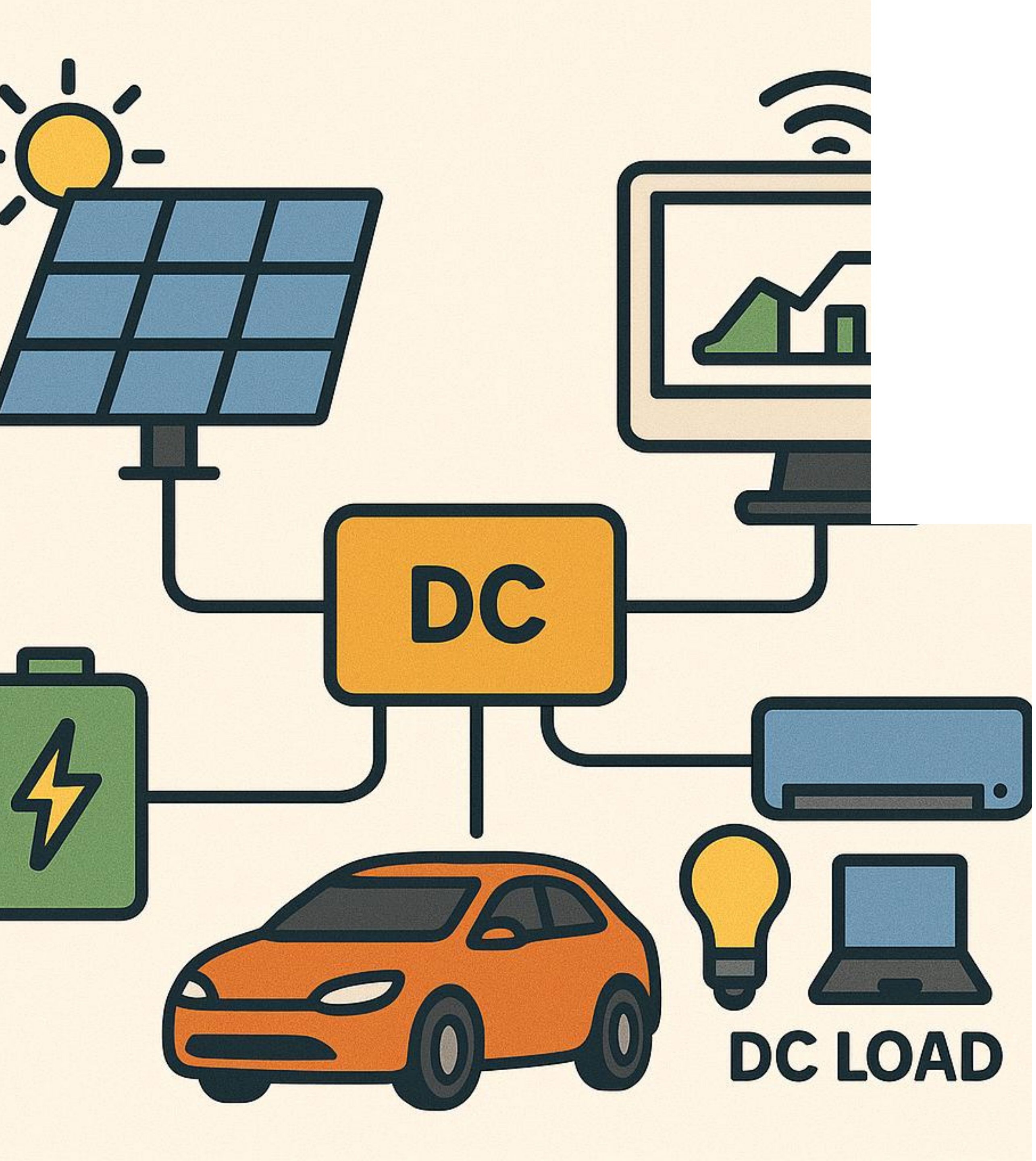
LIVE TELEMETRY: HTTPS://DCINNOHUB.COM/

*i*³ DC INITIATIVE: *i*nform, *i*nspire & *i*nnovate

i³ DC
Accelerates Energy Transition

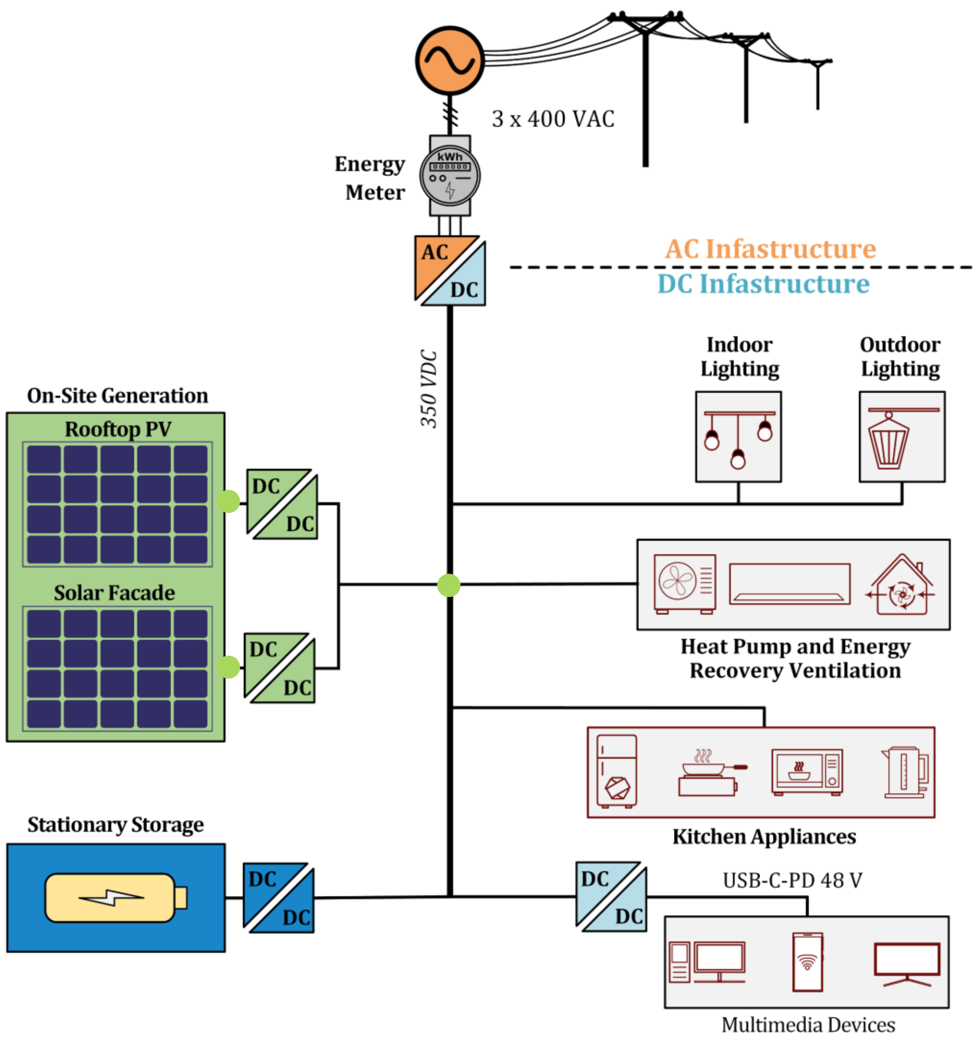
TAL TECH POWER ELECTRONICS GROUP
IEEE ESTONIA SECTION IES/PELS/IAS/PES JOINT SOCIETIES CHAPTER
Estonian Research Council
Centre of Excellence in Energy Efficiency

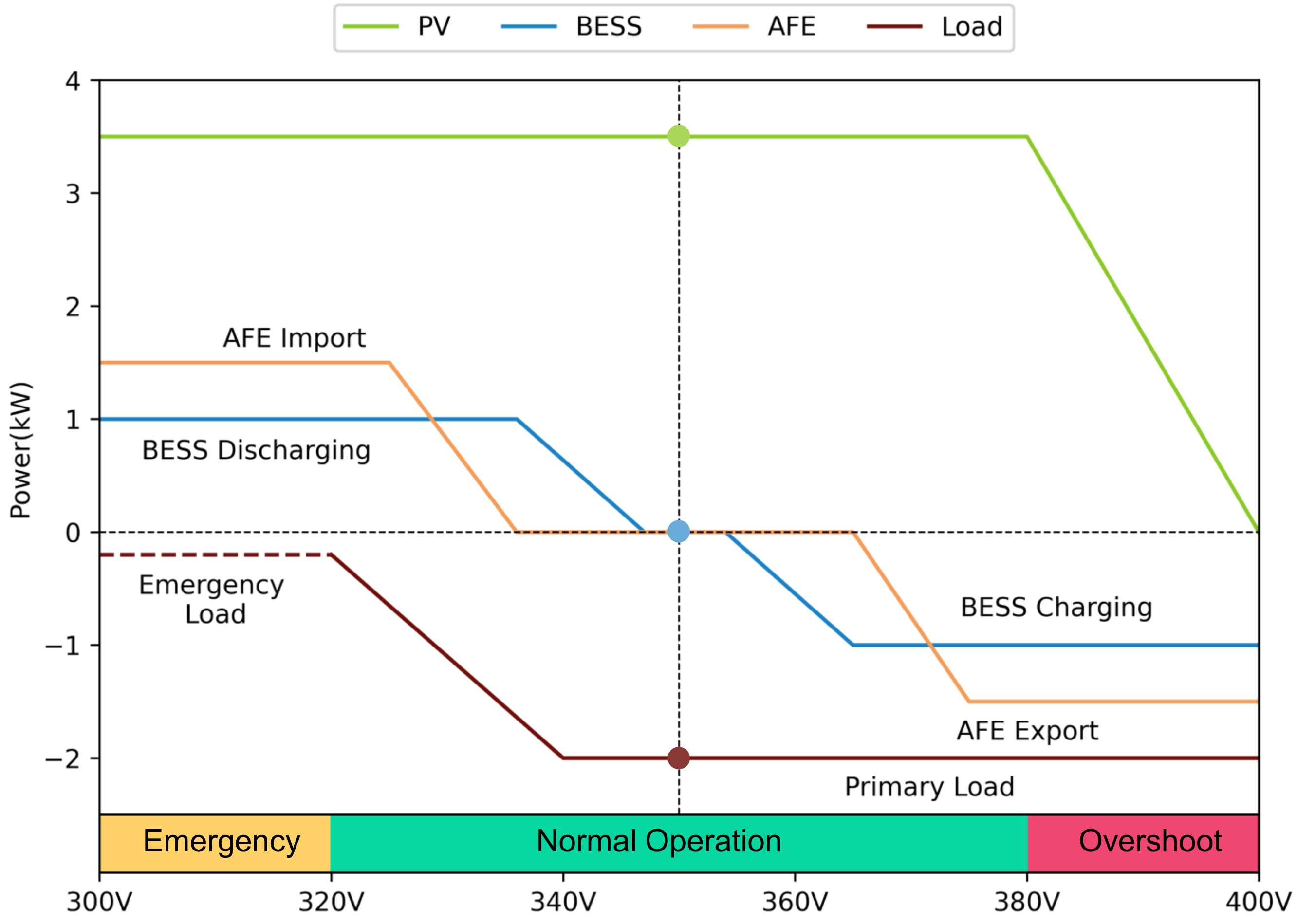
The 6th Estonian
DC Innovation Workshop
Shaping Estonia's DC Future



DROOP CONTROL BACKBONE OF POWER AND ENERGY MANAGEMENT

Full Irradiation

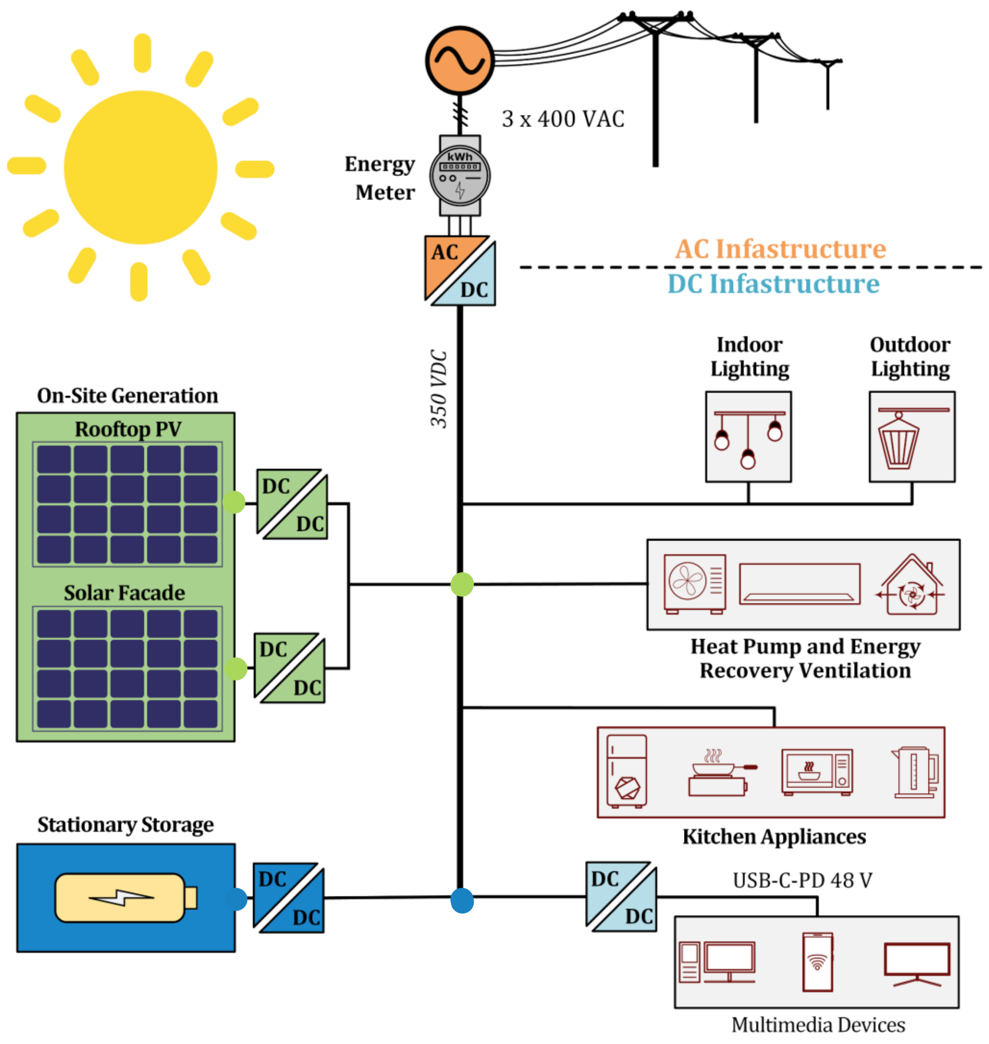


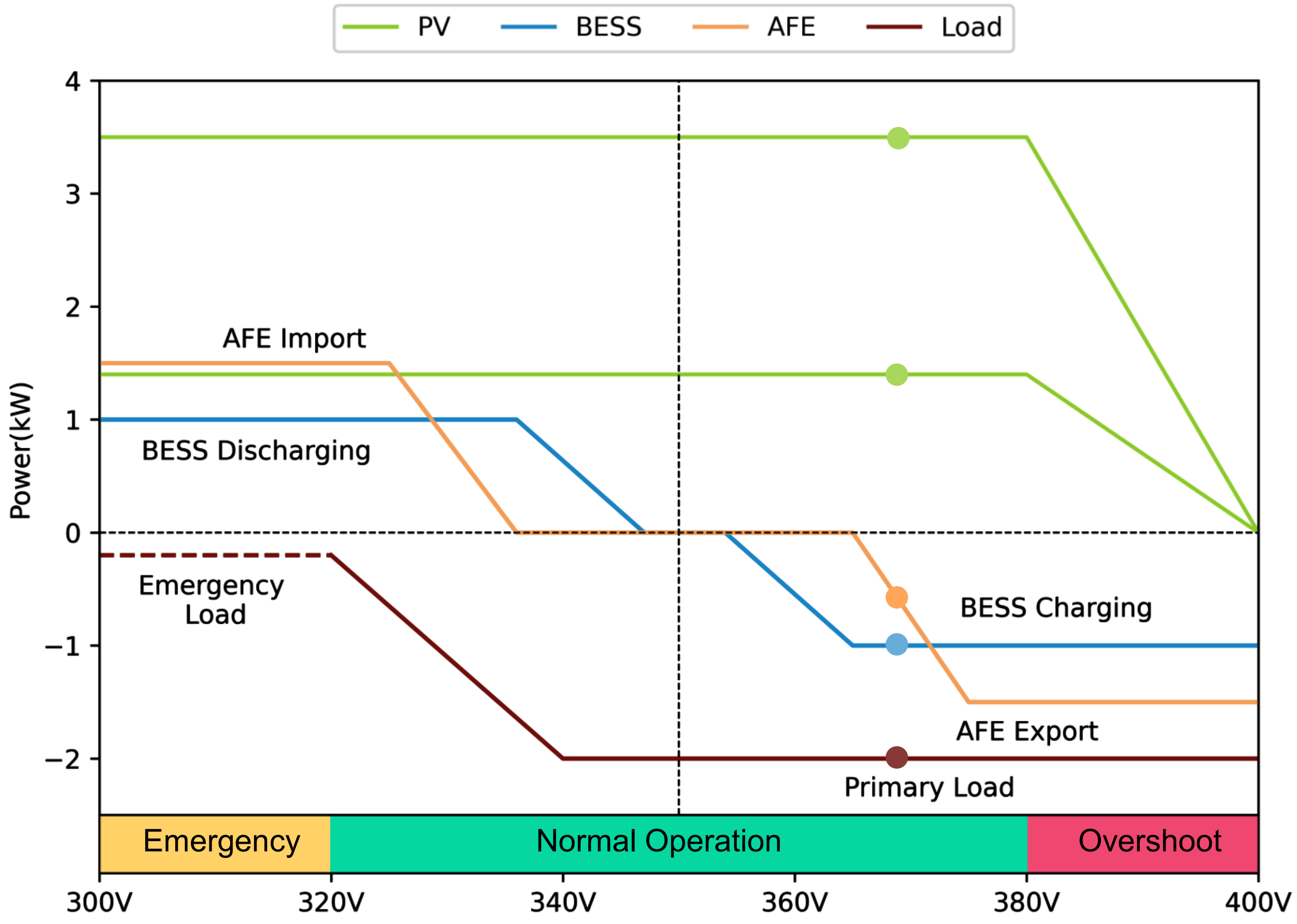


The example DC system is connected to AC grid through active front end (AFE) full-power converter and incorporates PV generation, battery storage and droop-controlled loads

The sun is shining, and the PV generation is high enough to supply all loads, provide power to battery charging and even export part of the energy to the AC grid.

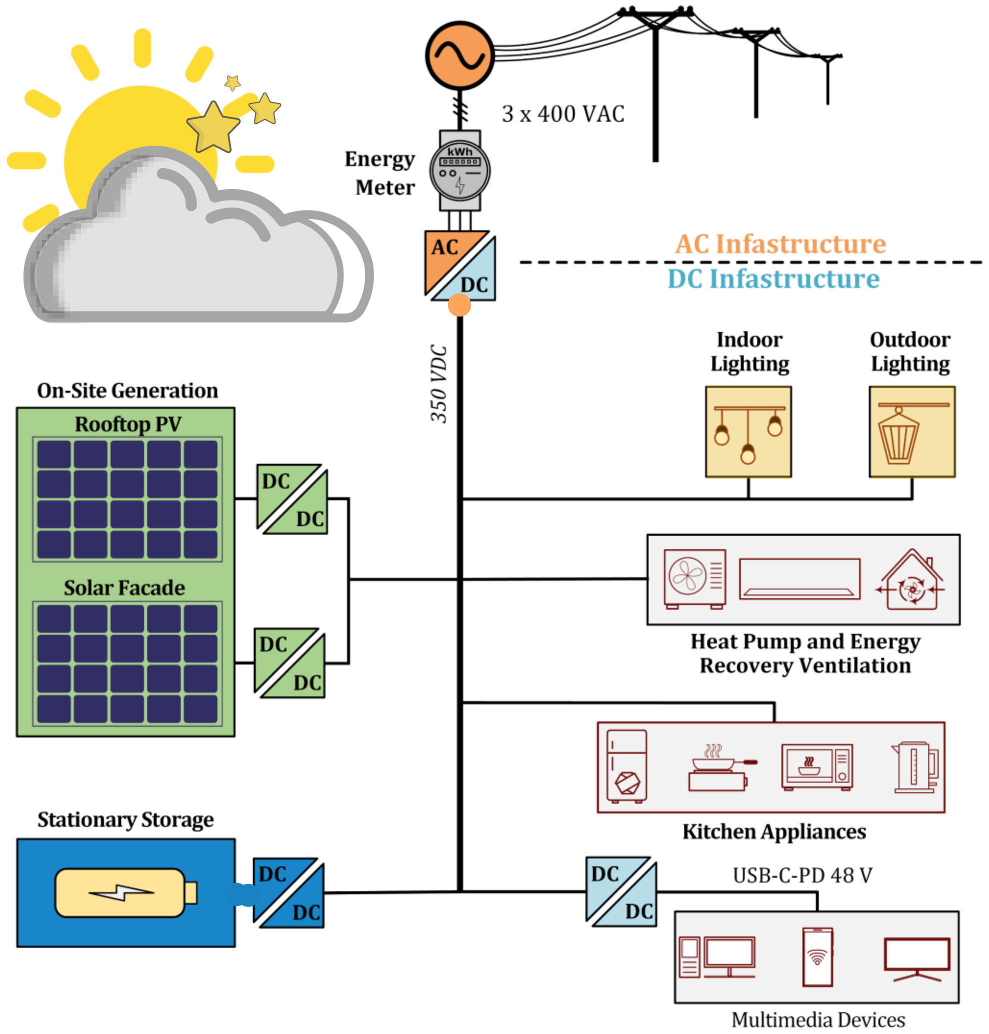
Partial Shading

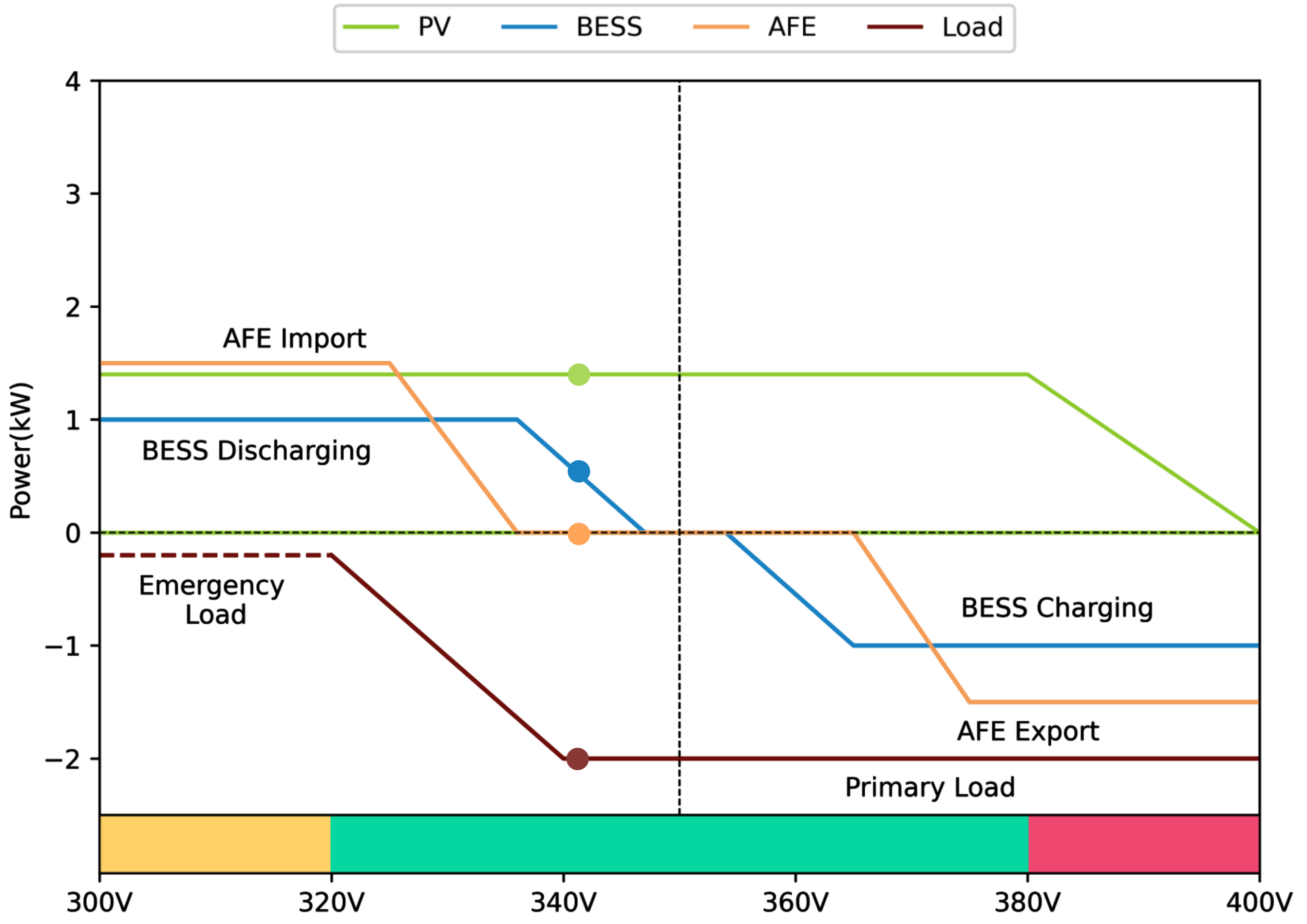




The clouds appear and the PV energy production falls. The battery now discharges to cover the load demand.

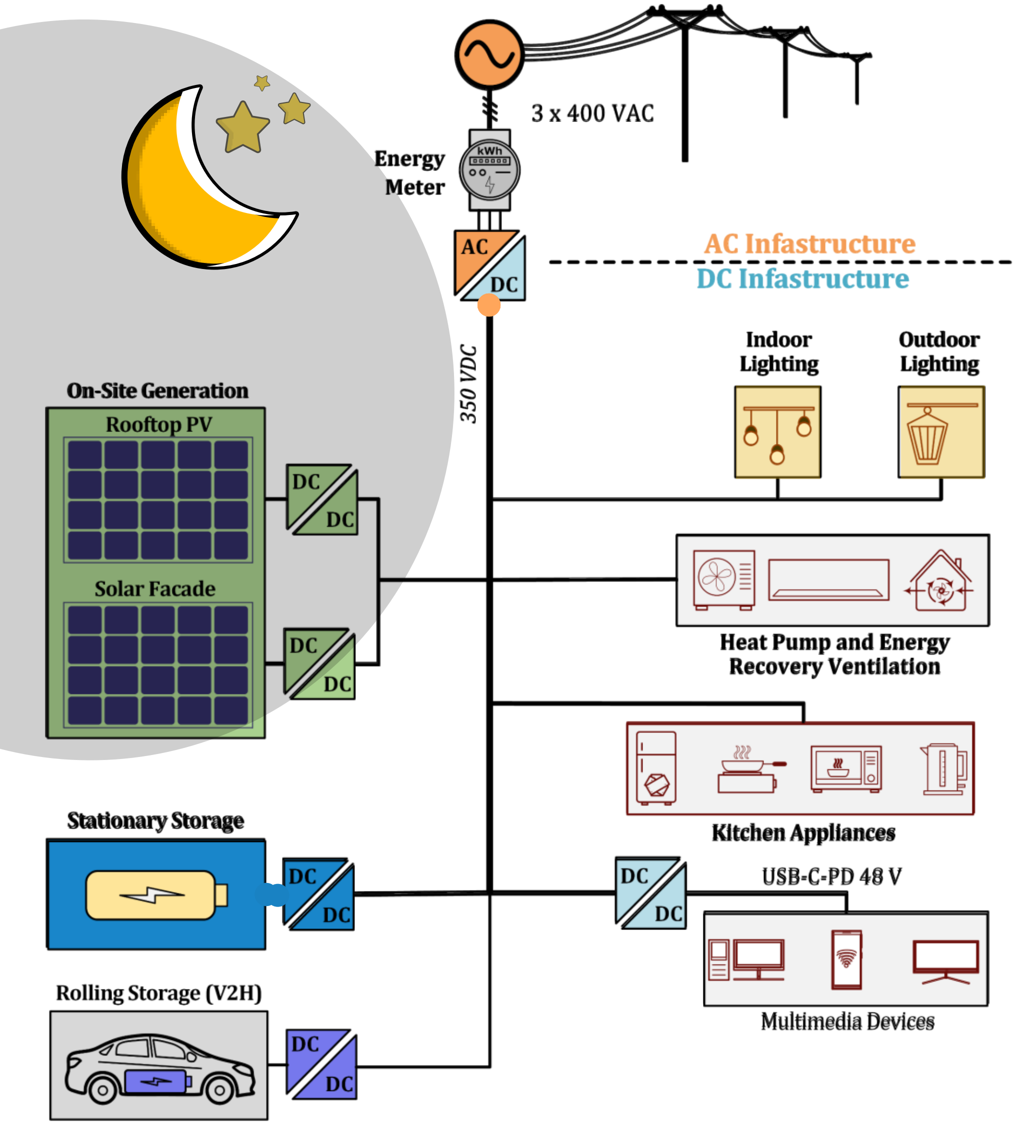
Night

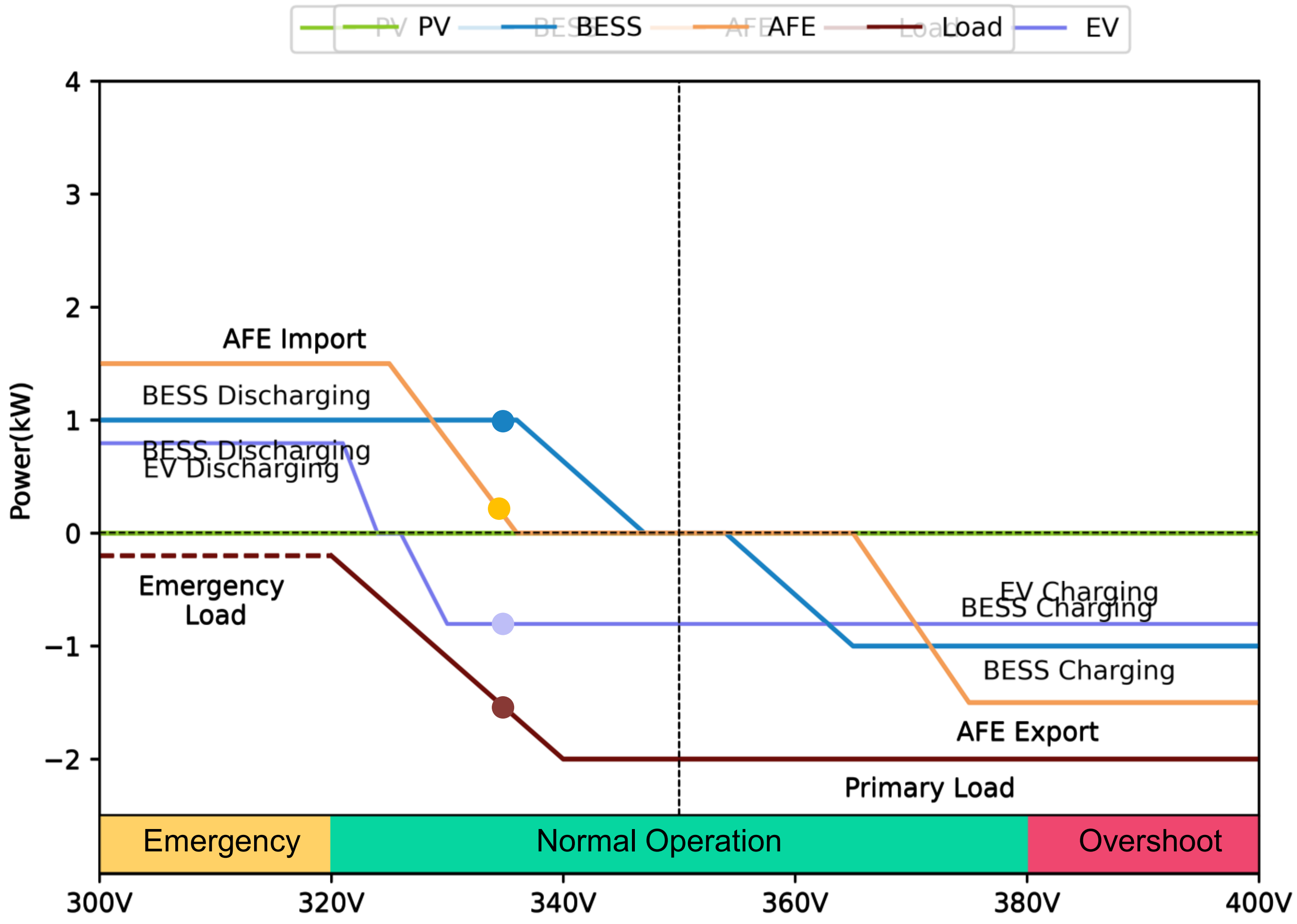




The nighttime starts and the PV production falls to zero. The battery operates at full power to supply the load. To attain energy balance, part of the energy is also imported from the AC grid by AFE, while the consumption of the non-critical loads is reduced

EV Charging

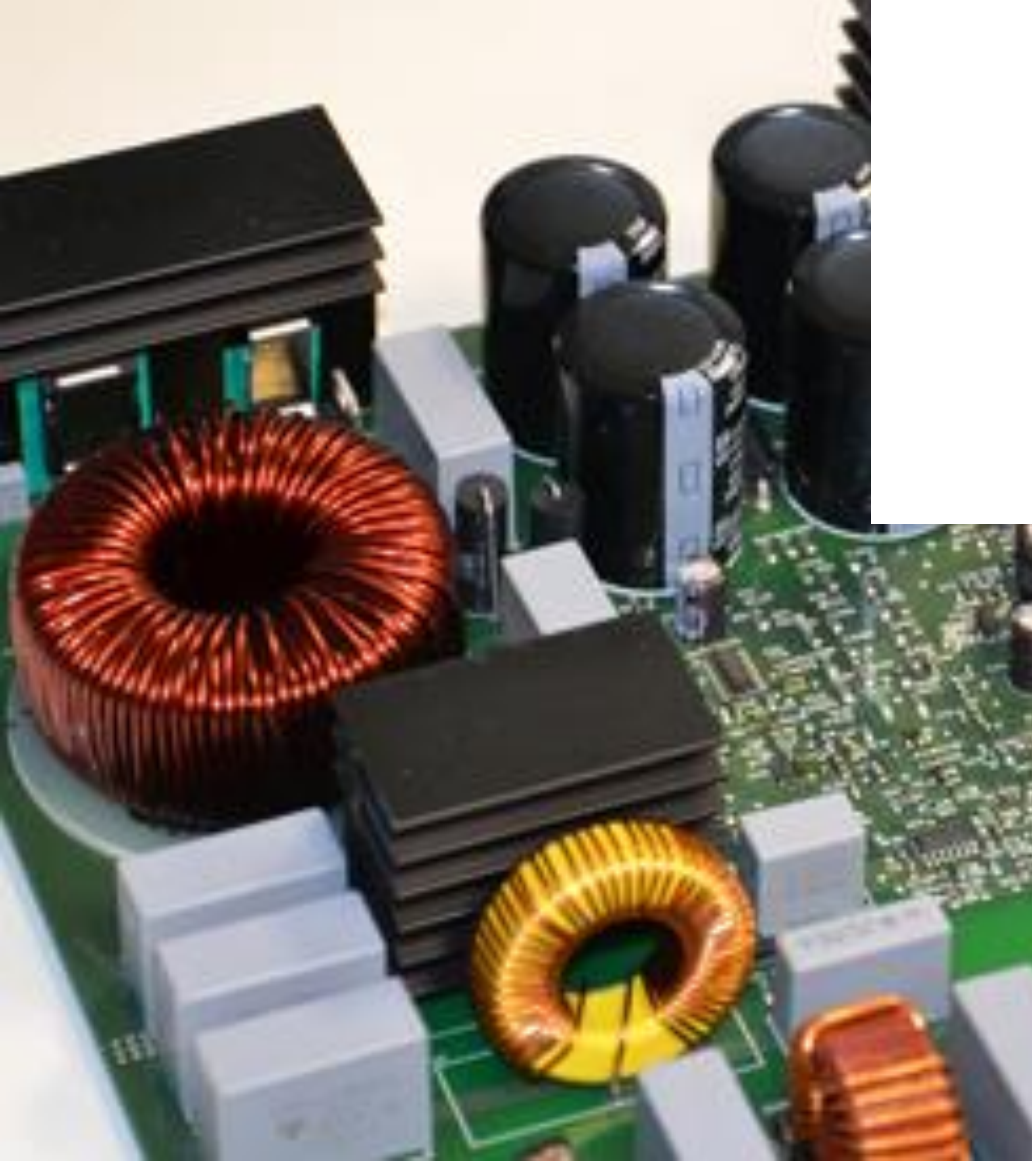




The addition of other components into the system results in changes in its behaviour and the droop profile needs to be re-evaluated. For example, the addition of EV with priority charging requires further reduction of primary load to attain energy balance.

ADOPTING HIERARCHICAL CONTROL

Layer	*Control Actions*	*Timescale*	*Hardware*
Tertiary Control	**Energy Management:** Optimizing power generation and consumption, Resource Prediction, Arbitrage, Black start priority scheduling	Minutes Hours Day	SBC FPGA
Secondary Control	**Power Management:** Power Balance, Voltage regulation/restoration, SOC Management	Seconds	COM link; Communi-cation MCU; **Droop Control**
Primary Control	**Voltage and current control**	Millsec Microsec	MCU; **Droop Control**

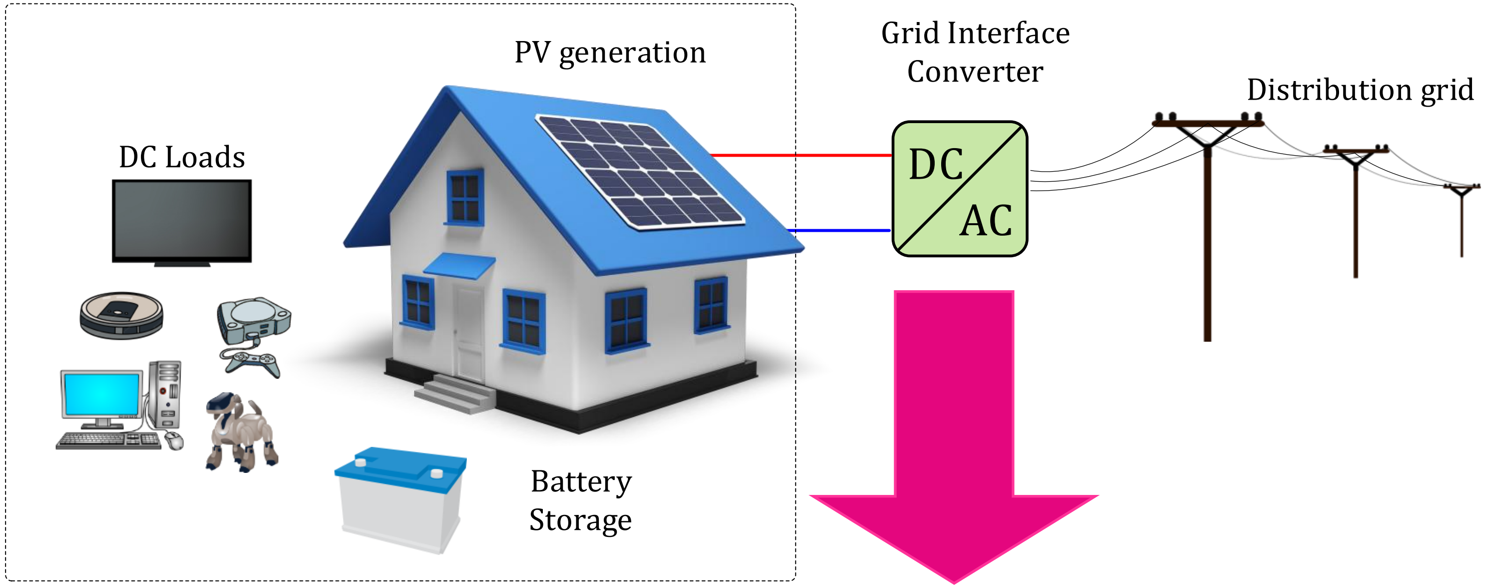


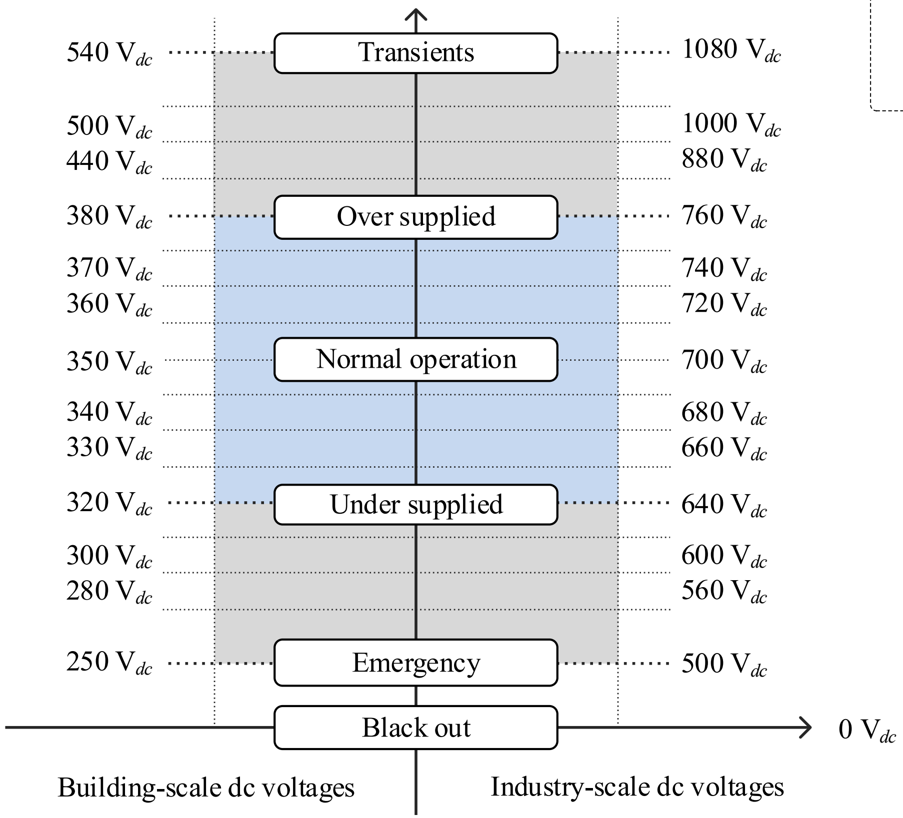
POWER ELECTRONICS ENABLING TECHNOLOGY FOR DC BUILDINGS

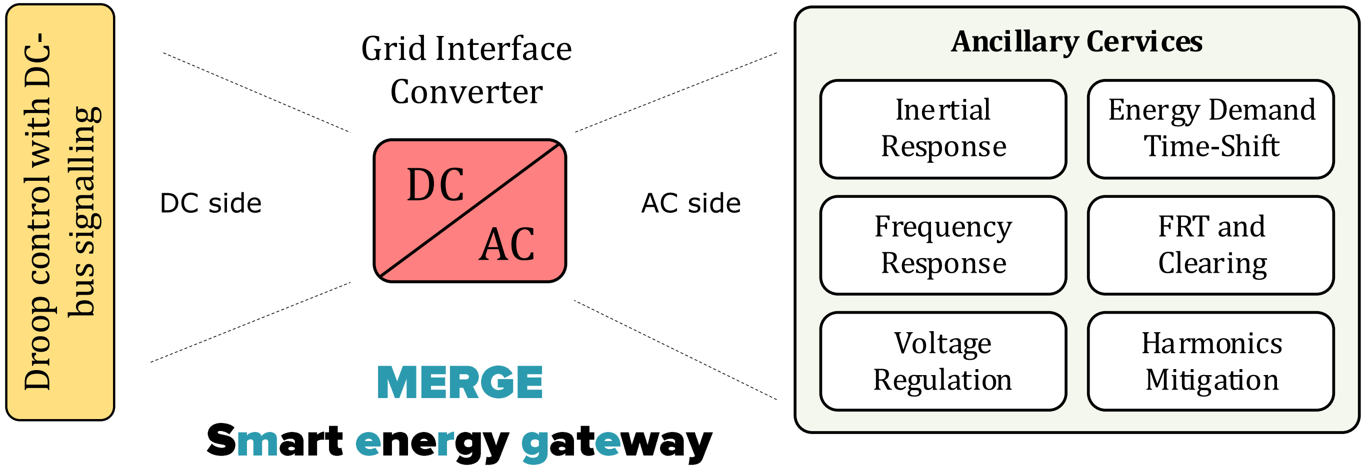
DC GRID FORMING CONVERTER

MAIN FUNCTIONS

- *Bidirectional power transfer*
- *AC grid support (like smart PV inverter)*
- *DC grid forming and droop control*





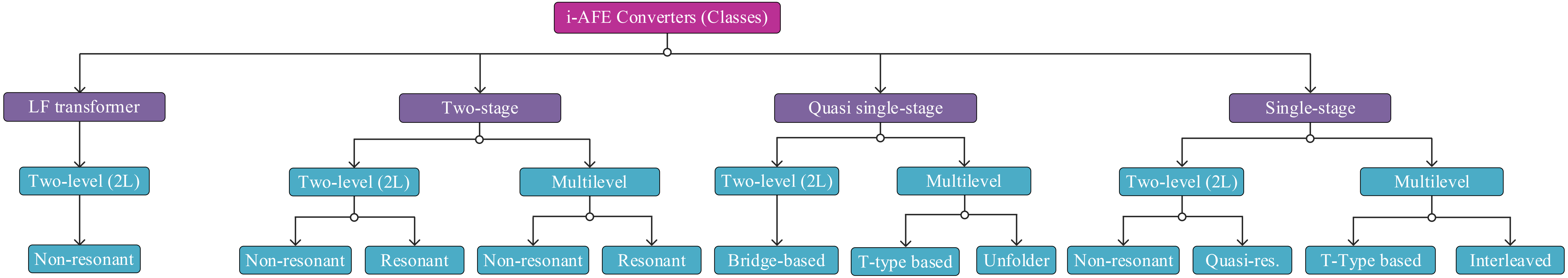


ACTIVE FRONT-END (AFE) AC-DC CONVERTERS

CLASSIFICATION ACCORDING TO THE NUMBER OF POWER PROCESSING STAGES

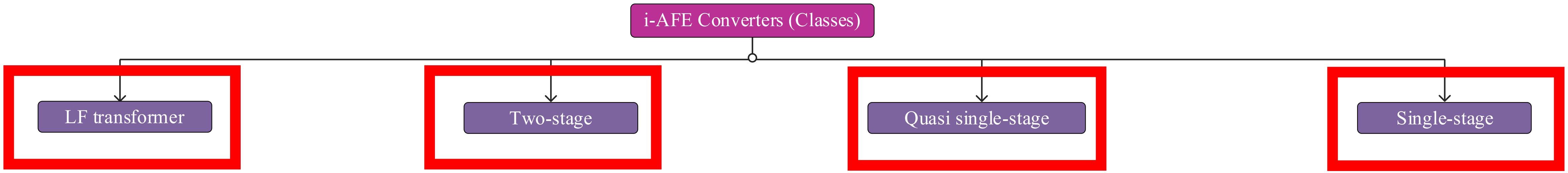
CurrentOS

“Faults and disturbances in the DC grid shall not propagate or cause malfunctions in the AC grid. In Current/OS this is ensured with galvanic isolation of the two grids. {…}
Therefore, in Current/OS installations ***only galvanically isolated converters*** shall be used for interfacing between the AC and the DC grid.“

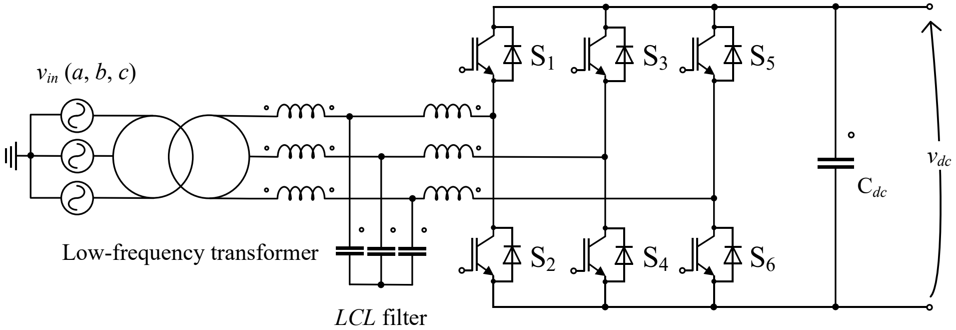


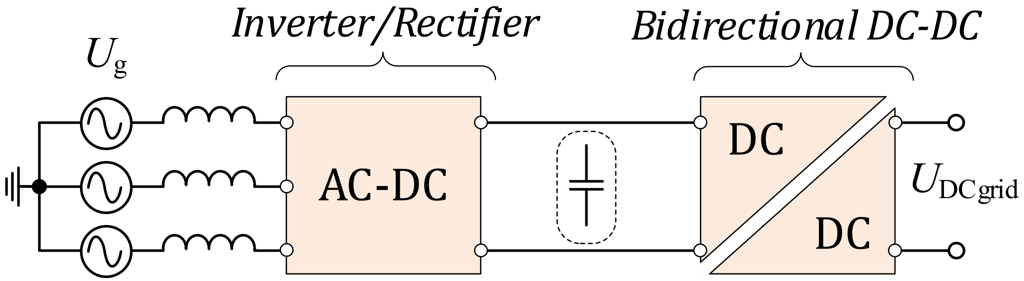
E. L. Carvalho, A. Blinov, A. Chub, P. Emiliani, G. de Carne and D. Vinnikov, "Grid Integration of DC Buildings: Standards, Requirements and Power Converter Topologies," in IEEE Open Journal of Power Electronics, vol. 3, pp. 798-823, 2022, doi: 10.1109/OJPEL.2022.3217741.

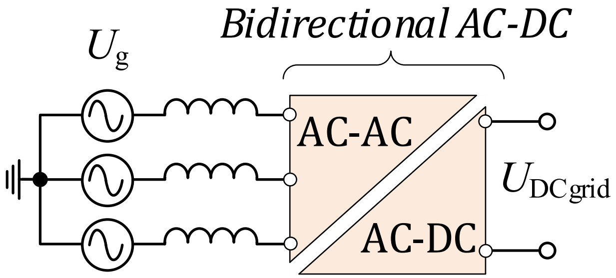
AFE AC-DC CONVERTER TYPES

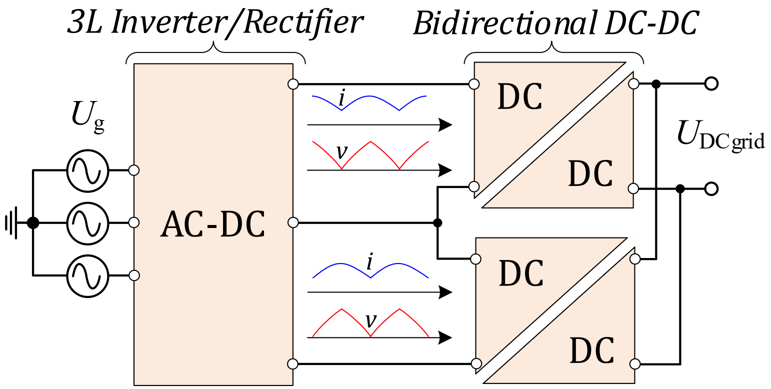


- *Bulky and heavy*
- *High use of materials*
- *Possible acoustic noise*



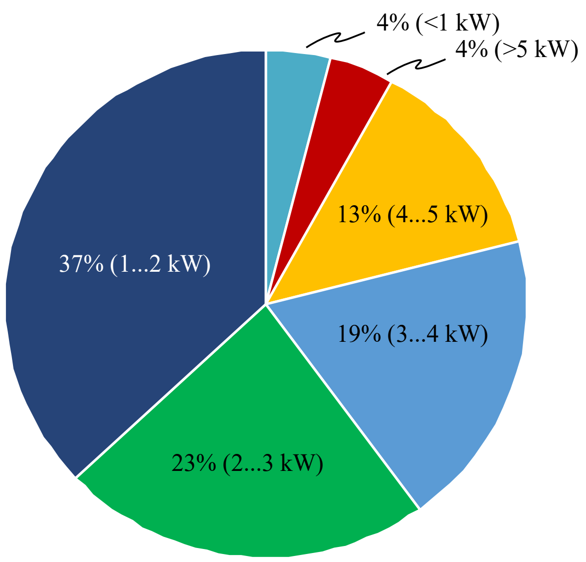




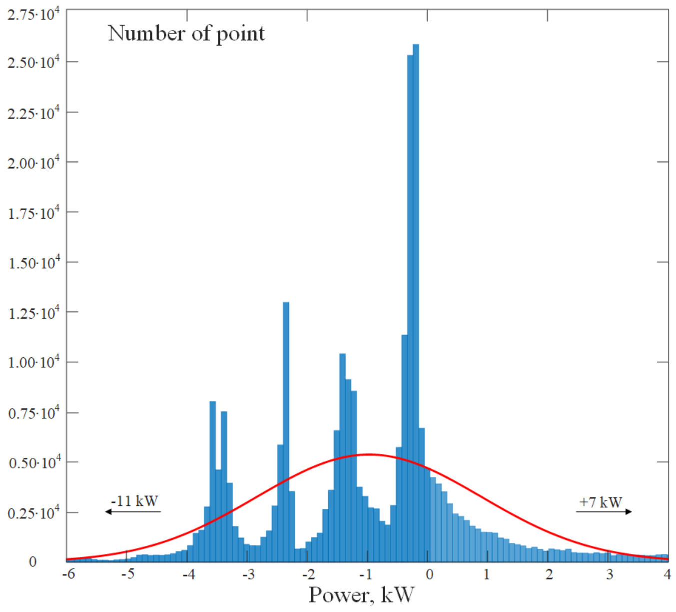


DC GRID FORMING CONVERTER DESIGN ASPECTS

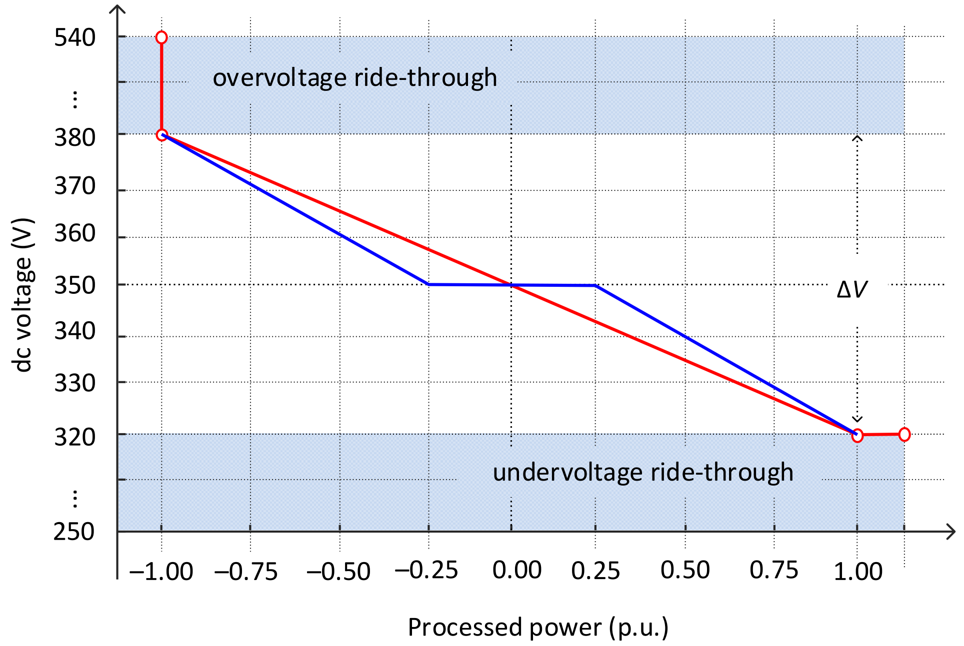
Energy consumption profile



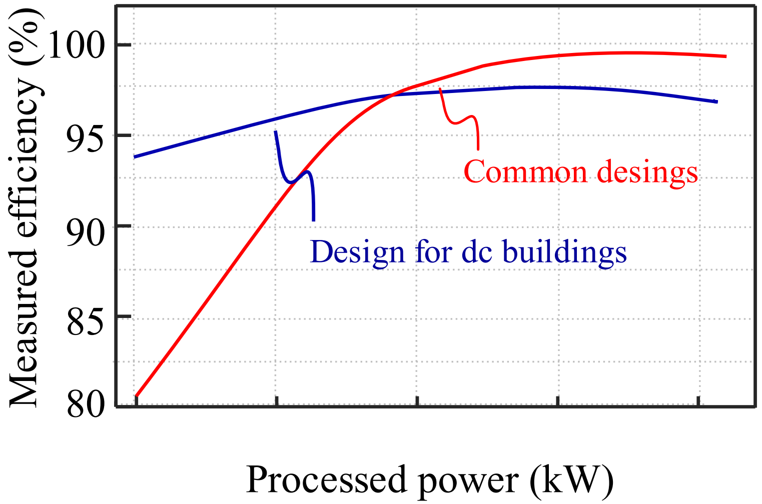
Load profile



Droop profile



Efficiency profile



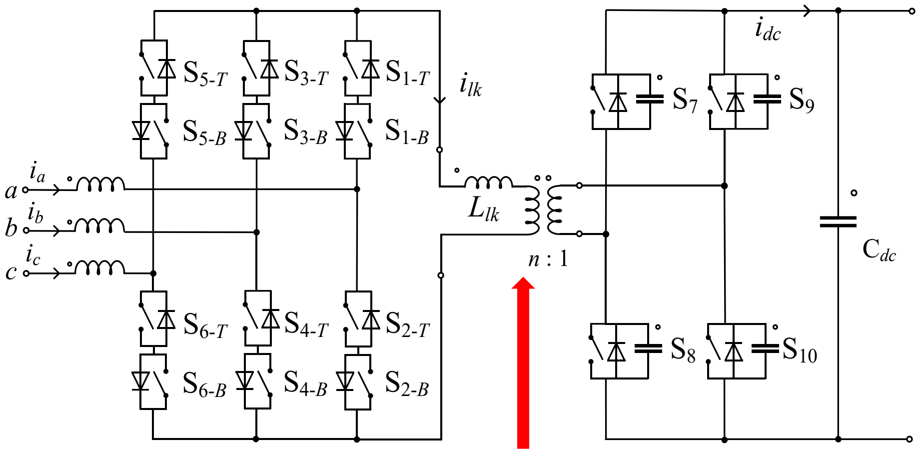
Design targets and priorities

- *Investigate actual operational profile*
- *Indicate most probable working conditions*
- *Optimize the design considering the droop curve*

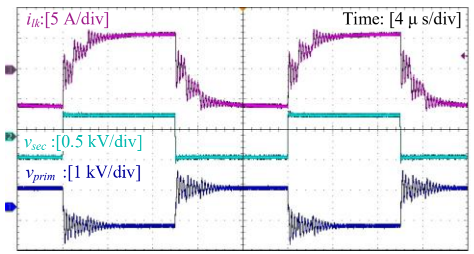
E. L. Carvalho, A. Sidorova, A. Blinov, A. Chub and D. Vinnikov, "Design Considerations of Dual-Active Bridge DC Grid-Forming Converter for DC Buildings," in *IEEE Transactions on Industrial Electronics*, doi: 10.1109/TIE.2023.3331125.

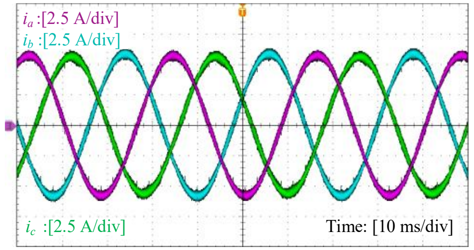
TAL TECH

EXAMPLE DESIGNS: AC-DC MATRIX-CONVERTER



High-Frequency AC Link

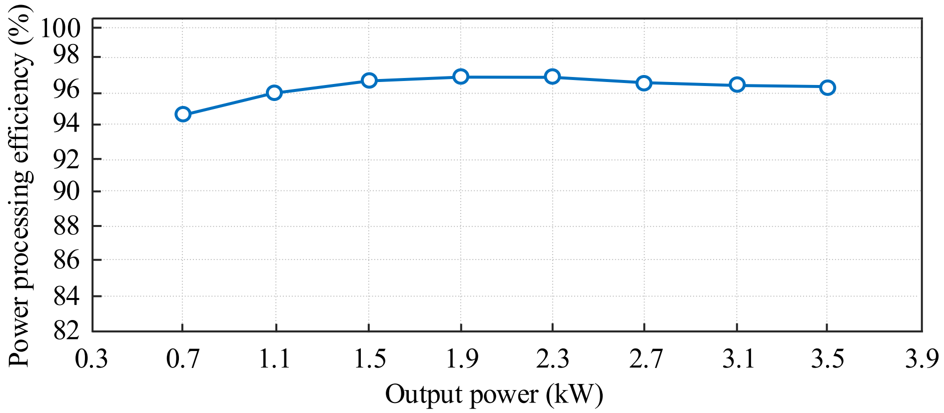




Single-stage isolated matrix converter

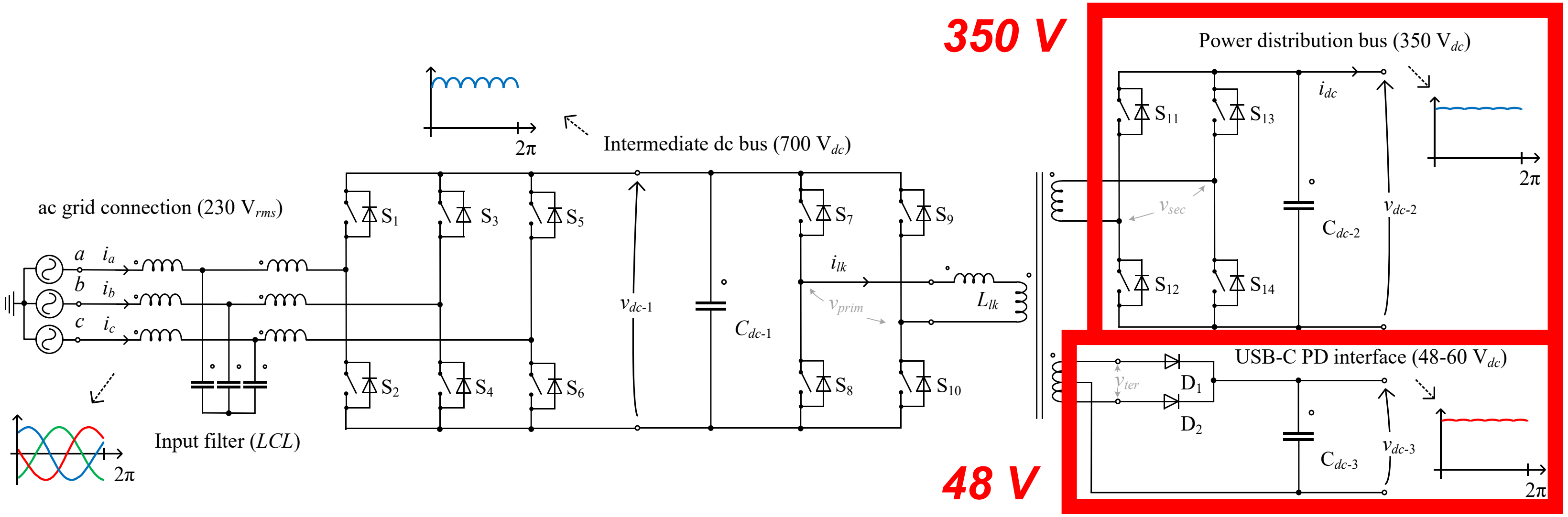
- *Peak efficiency 96.7%*
- *High efficiency at low power thanks to soft switching*
- *No intermediate DC*

Parameter/component	Value/Specification
Input voltage (*ac*)	230 V_{rms} (phase-neutral)
Nominal power (*P*)	3.5 kW
ac filter (*L*)	1.3 mH
Allowed *THD*	5 %
Primary side switches (S_1-S_6)	IMW120R220M1H (1200 V/9.5 A)
Secondary side switches (S_7-S_{10})	C3M0120065k (1200 V/22 A)
Switching frequency (f_s)	50 kHz
HF transformer	Pri: 31 turns Sec: 17 turns Turns ratio (*n*:1): 1.82: 1 Core: 2 × TDK EPCOS N87 Leakage inductance: 8 µH
Output voltage (*dc*)	350 V_{dc} (following NPR9090)
Output current (i_{dc})	10 A
Output capacitance (C_{dc})	60 µF
Driver circuits	UCC21521



E. L. Carvalho, A. Blinov, P. Emiliani, A. Chub and D. Vinnikov, "Three-Phase Bidirectional Isolated AC–DC Matrix-Converter With Full Soft-Switching Range," in *IEEE Access*, vol. 11, pp. 119270-119283, 2023, doi: 10.1109/ACCESS.2023.3327224.

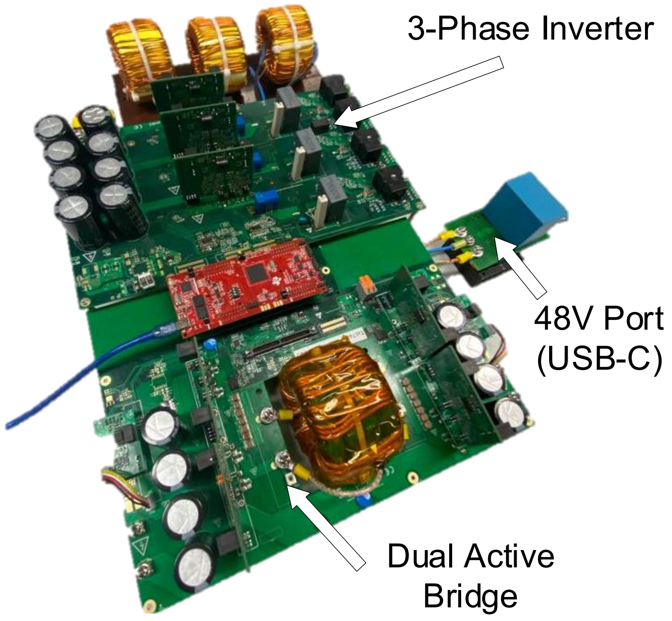
EXAMPLE DESIGNS: TWO-STAGE MULTI-PORT



Parameter/Component	Value/Detail
2L-VSC converter (ac-dc stage)	
ac voltage	230 V_{rms} (phase-neutral)
Nominal power	5.36 kW
LCL filter (ac side)	350 µH – 4.7 µF – 15 µH
Switches (S_1-S_6)	C2M0160120D (1200 V/19 A)
Switching frequency (f_s)	20 kHz
Intermediate dc bus ($v_{dc\text{-}1}$)	700 V_{dc}
Main isolated dc-dc stage	
Output voltage ($v_{dc\text{-}2}$)	350 V_{dc}
Output power (P_2)	5 kW (nom.)
Modulation method	Phase-shift modulation
Phase-shift range	$-\pi/6 \leq \delta \leq \pi/6$
Switching frequency (f_s)	100 kHz
Input capacitor (C_1)	2 mF
Output capacitor (C_2)	470 µF
Primary side switches (S_7-S_{10})	C2M0160120D (1200 V/19 A)
Secondary side switches (S_{11}-S_{14})	C3M0120065D (650 V/22 A)
USB PD interface	
Output voltage ($v_{dc\text{-}3}$)	48-60 V_{dc}
Output power (P_3)	360 W (nom.) / 7.5 A (max.)
Output capacitor (C_3)	60 µF
Diodes (D_1-D_2)	RURG8060
Complementary components	
HF transformer	Pri: 24 turns Sec: 12 turns Ter: 5 turns Turns ratio (*n*:): 2:1:0.21 Core: 4×B64290L0730 (N87) Leakage inductance: 78 µH
Driver circuits	UCC21521

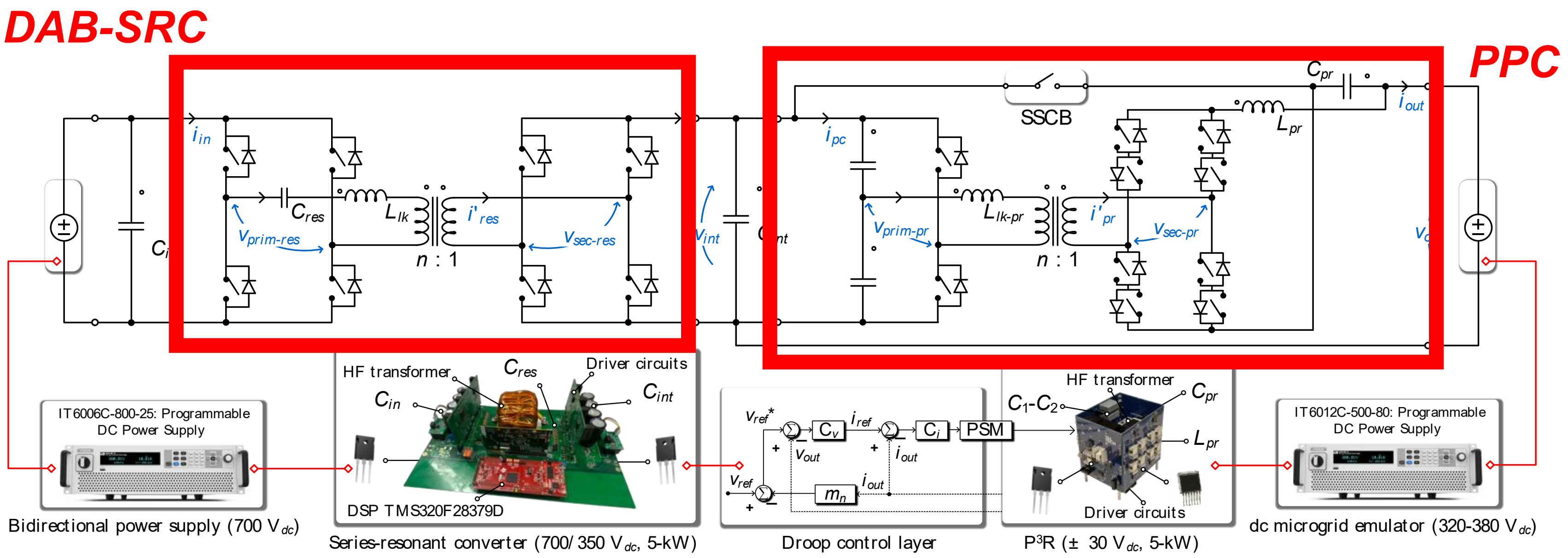
Multiport converter:

- *Utilizes single 3-w transformer*
- *Regulation according to droop curve*
- *95.6% efficiency at 350V port*
- *92.8% efficiency at 48V port*



E. L. Carvalho, A. Blinov, A. Chub, I. Galkin and D. Vinnikov, "Multi-port i-AFE Converter for Grid-Interactive Buildings: Design Requirements and Efficiency Evaluation," 2023 IEEE 8th Southern Power Electronics Conference and SPEC/COBEP, Florianopolis, Brazil, 2023, doi: 10.1109/SPEC56436.2023.10408230.

EXAMPLE DESIGNS: P3R CONVERTER

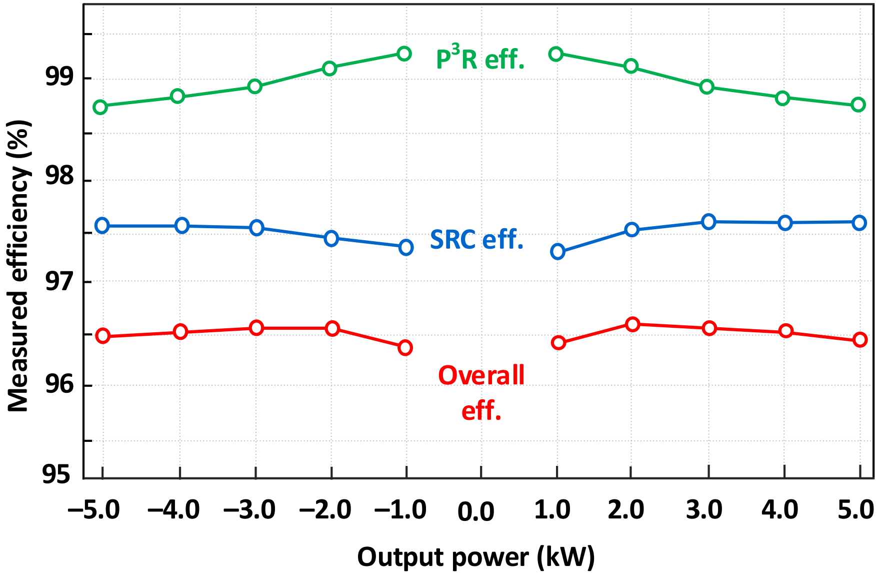


Parameter/Component	Value/Detail
Rated power (P_o)	5 kW
Input dc voltage (v_{in})	700 V_{dc}
Output dc voltage (v_{int})	350 V_{dc}
Output current (i_{out})	14.29 A
Switching frequency (f_s)	100 kHz
Quality factor (Q)	$0.1 < Q < 0.6$
Input capacitor (C_{in})	220 µF
Intermediate capacitor (C_{int})	470 µF
Primary side switches	UF3SC120009K4 (1200 V/65 A), 73 mΩ /210 pF
Secondary side switches	UF3SC065007K4 (650 V/120 A), 8.8 mΩ /1190 pF
HF transformer	Pri: 24 turns Sec: 12 turns Turns ratio (n:1): 2:1 Core: 4×B64290L0730 (N87)
Leakage inductance (L_{lk})	90 µH
Series capacitor (C_{res})	28 nF (1 kV)

Parameter/Component	Value/Detail
Rated power (P_o)	5 kW
Output current (i_{out})	14.29 A
Output dc voltage (v_{out})	320…380 V_{dc}
Switching frequency (f_s)	50 kHz
HF transformer	Pri: 23 turns Sec: 10 turns Turns ratio (n:1): 2.3: 1 Core: ETD54/28/19/3C97 Leakage inductance: 0.85 µH
Output capacitor (C_{pr})	100 µF
Output capacitor (L_{pr})	100 µH
Primary side switches	C3M0120090J (900 V/22 A) 170 mΩ /48 pF
Secondary side switches	BSC0403NS (40 V/98 A) 2.5 mΩ /500 pF
SSCB switches	G3R60MT07D (750 V/43 A) 60 mΩ /98 pF
Driver circuit	UCC21521

P³R converter:

- *Utilizes SRC in open loop*
- *Regulation according to droop curve by PPC*
- *Flat 96.5% efficiency characteristic*



E. L. Carvalho, A. Chub, N. Hassanpour, A. Blinov, A.K. Rathore and D. Vinnikov, "P3R – Partial Power Post-Regulated Grid Forming Converter for Prosumer DC Buildings," in *IEEE Transactions on Industrial Electronics* // Accepted, in press //.

BUILDING INTEGRATED PV (BIPV)

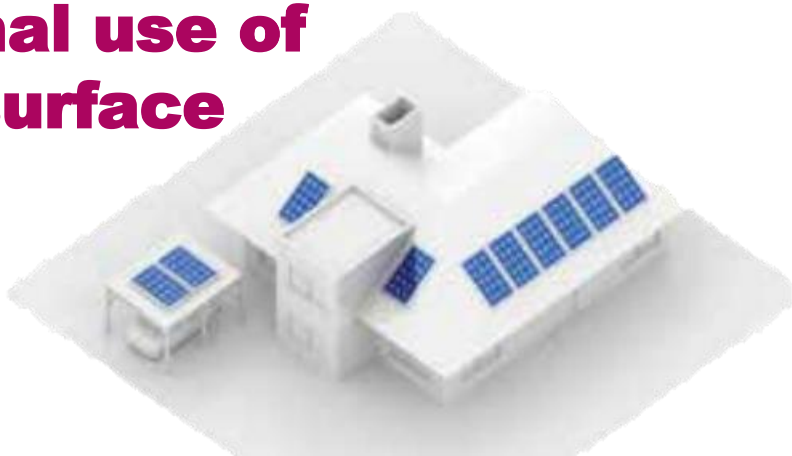
SOLAR ROOFS AND ROOF ATTACHED PV

RESIDENTIAL SYSTEM DESIGN – CHALLENGES

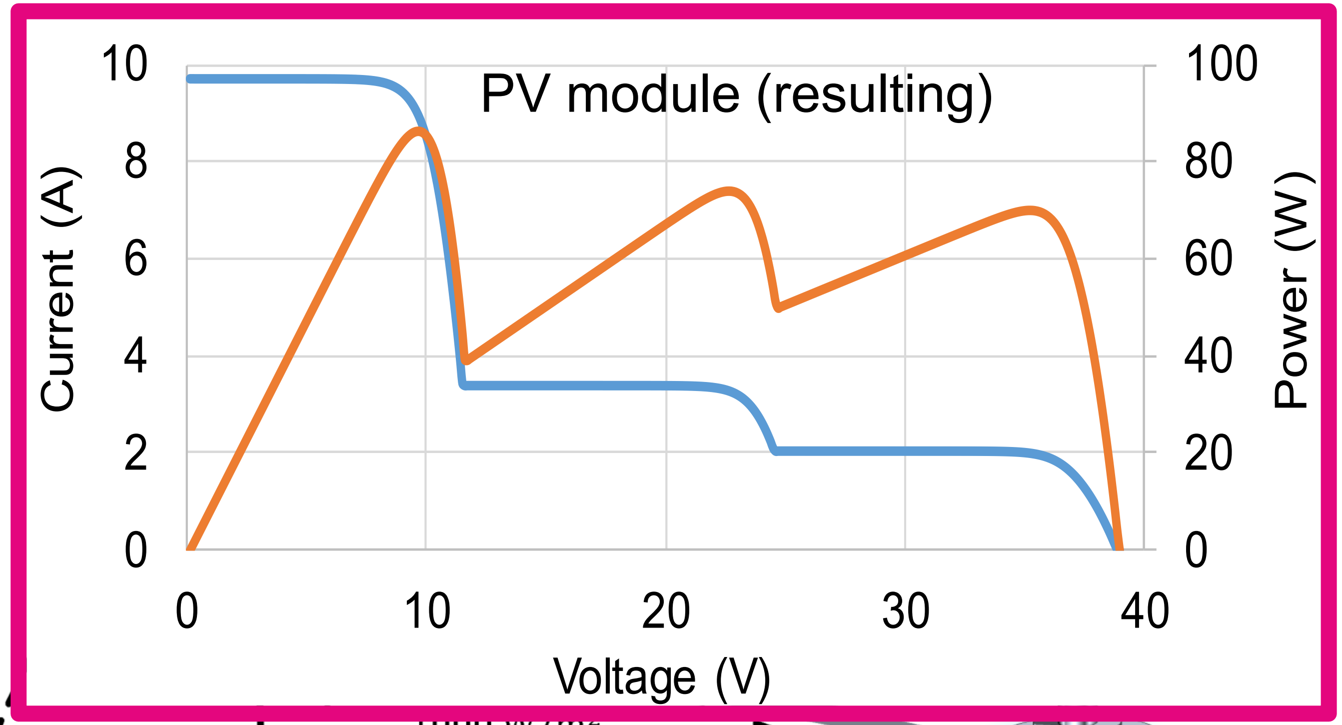
Partial shading

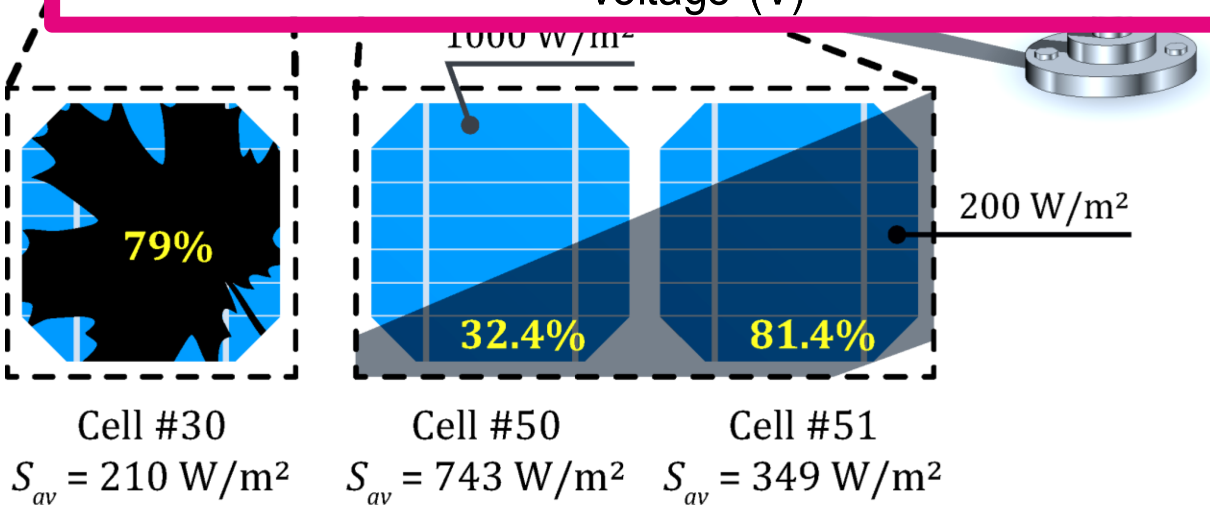
Multiple orientations

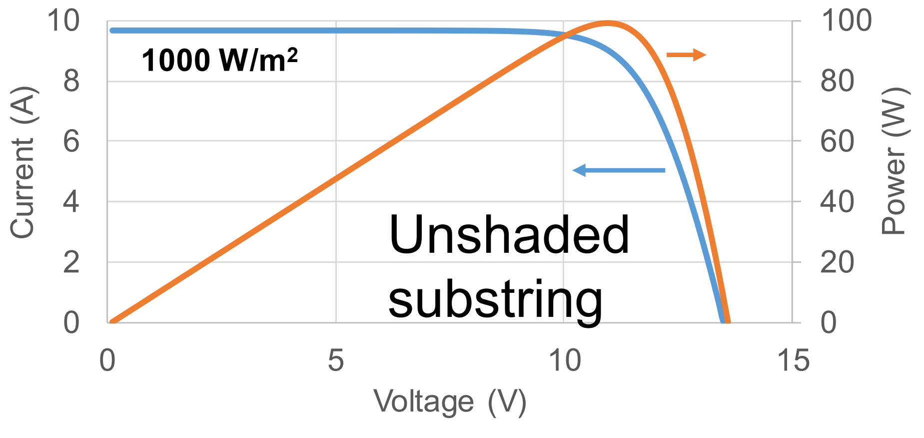
Optimal use of roof surface

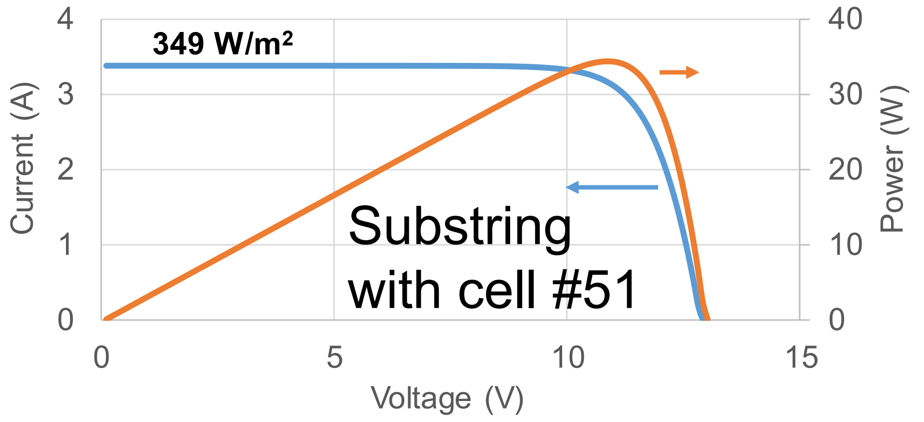


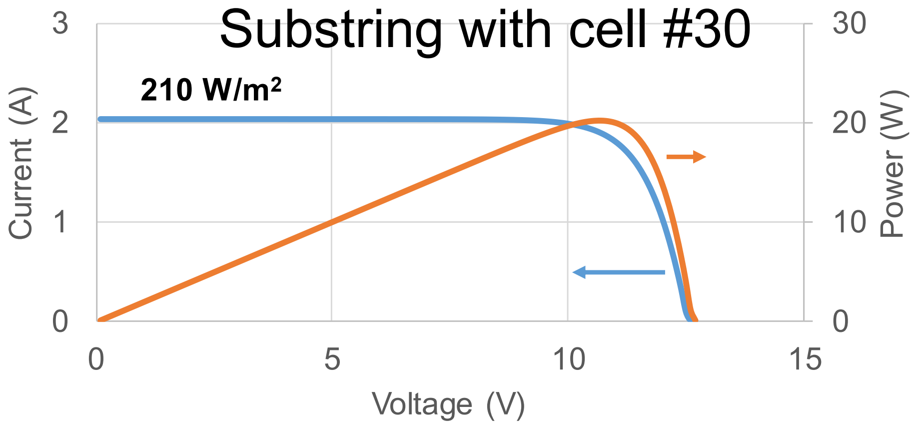
CHALLENGE - PARTIAL SHADING



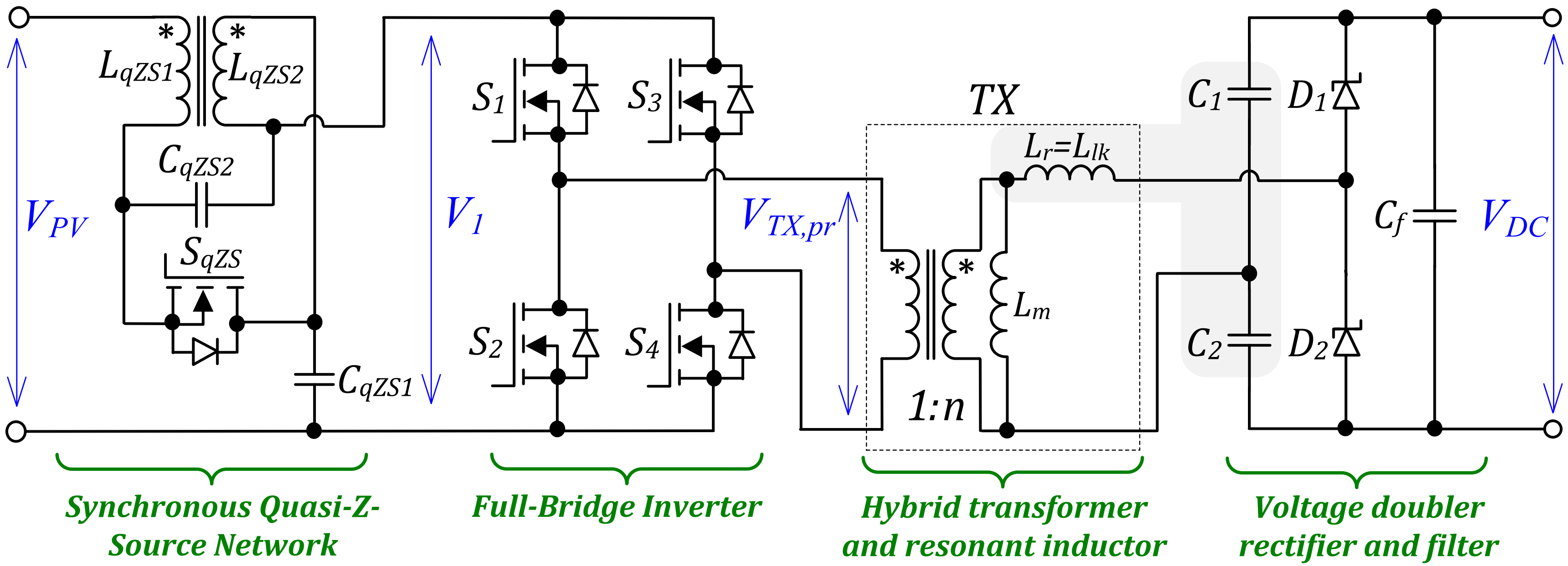






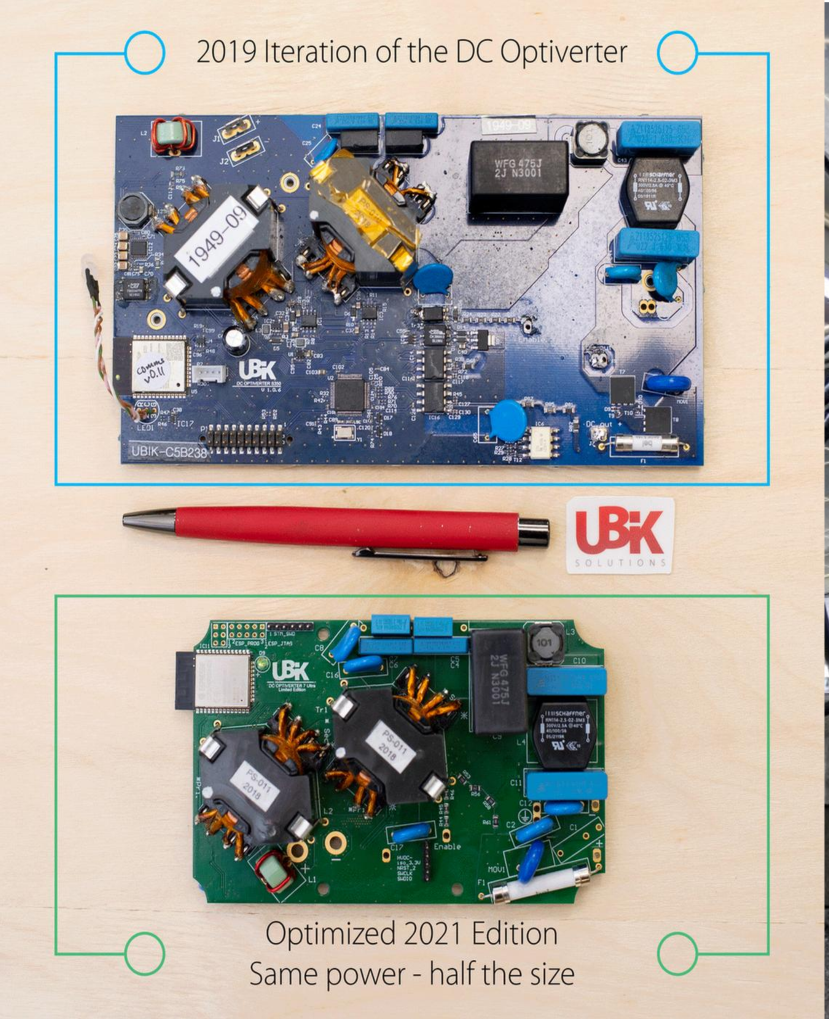


SOLUTION – QUASI-Z-SOURCE CONVERTER



- ❑ *Ultra-wide input voltage regulation range (8…60 VDC) thanks to hybridization of operating modes and advanced multi-mode control*
- ❑ *Voltage boost and buck functions in a single switching stage – no need for additional converters for the buck-boost functionality*
- ❑ *Inherent shoot-through and open state immunity*
- ❑ *Magnetically integrated synchronous quasi-Z-source network - continuous input current*
- ❑ *Fully integrated series resonant tank at the secondary side: leakage inductance of the transformer in series with VDR capacitors*

OPTIVERTER – A Hybrid of Photovoltaic OPTImizer and MicroconVERTER



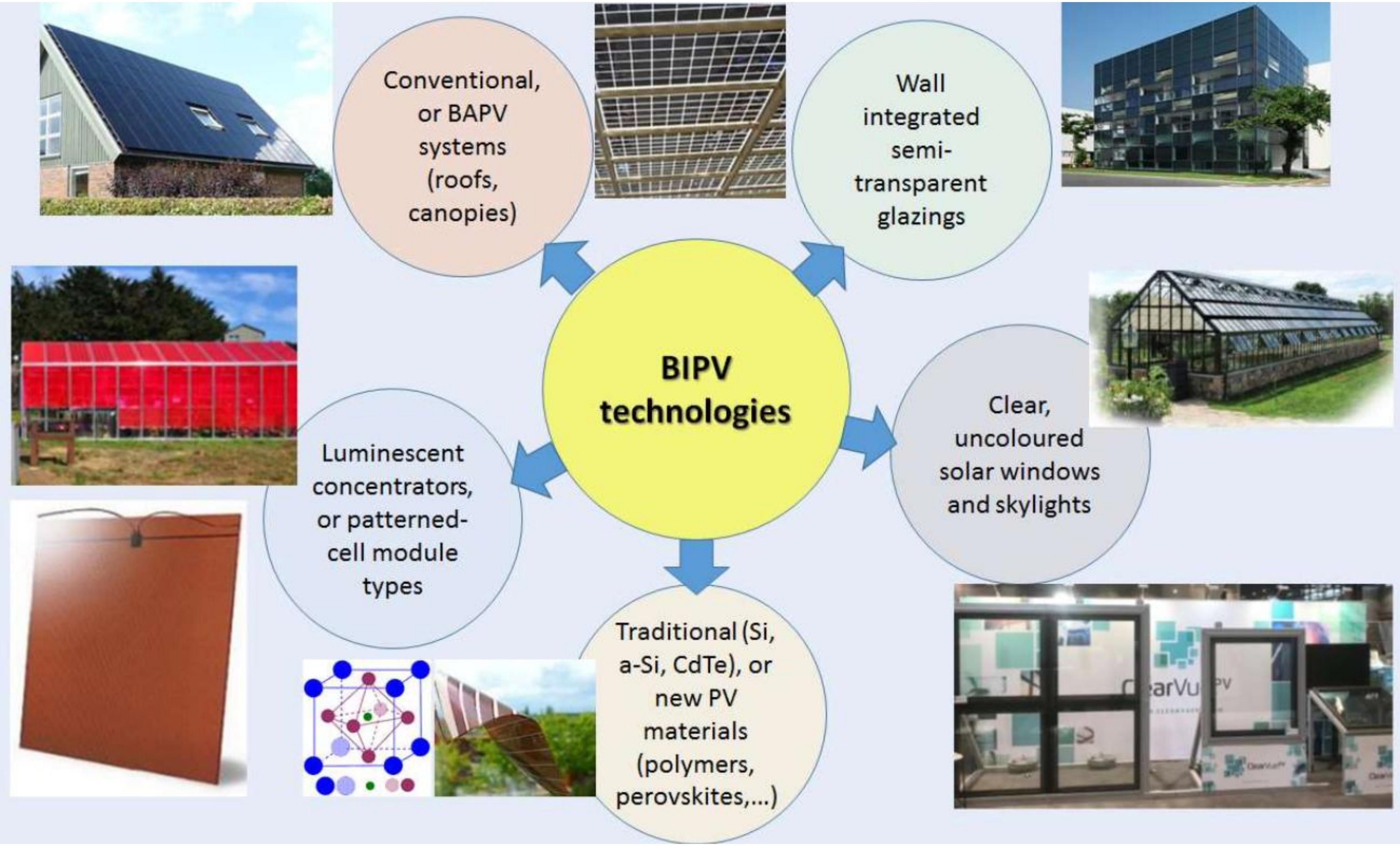
- *An entirely **novel PV MLPE technology***
- *Can be paired with all commercial **60- and 72-cell** PV modules*
- ***Fast GMPPT** and ultimate shade tolerance resulting in up to 30% better energy harvest*
- *Can be plugged either in **the 350 VDC or in 700 VDC** microgrids*
- ***Fully compatible** with emerging NPR9090 standard and Current OS DC microgrid protocol*
- *Supports the **droop control** functionality and features the integrated **solid state protection** circuitry for ensuring the highest level of fire and electric shock safety*
- ***All-in-One approach** with integrated gateway*
- *Integrates **2.4 GHz WiFi** and **BLE** for effortless cloud monitoring and on-site commissioning*

D. Vinnikov, A. Chub, E. Liivik, R. Kosenko and O. Korkh, "Solar Optiverter—A Novel Hybrid Approach to the Photovoltaic Module Level Power Electronics," in IEEE Transactions on Industrial Electronics, vol. 66, no. 5, pp. 3869-3880, May 2019, doi: 10.1109/TIE.2018.2850036.

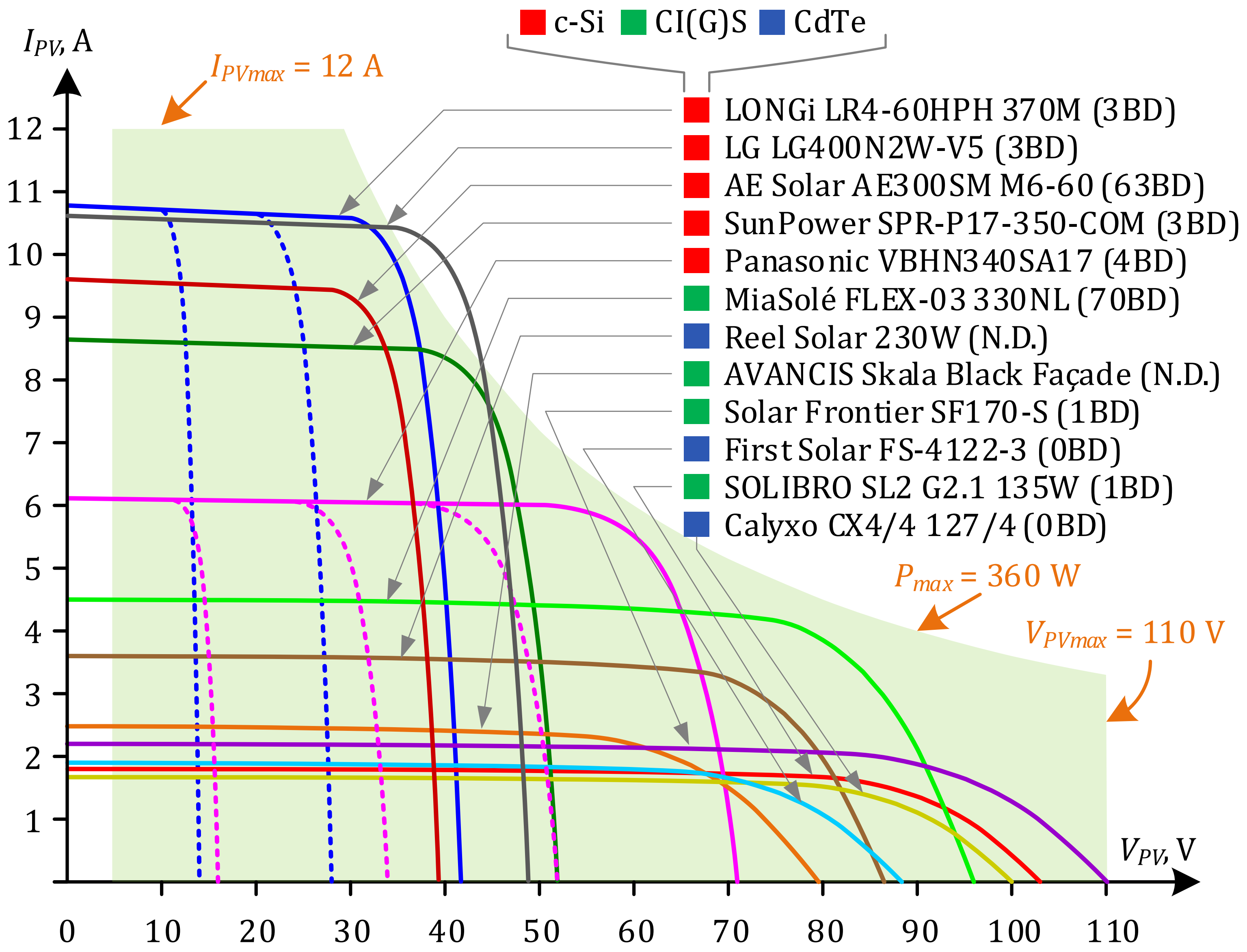
BUILDING INTEGRATED PV (BIPV) UNIVERSALIZATION OF THE INTERFACE CONVERTERS

BIPV SOLUTIONS

Source doi:10.3390/en12061080



CHALLENGE - VARIETY OF BIPV SOLUTIONS

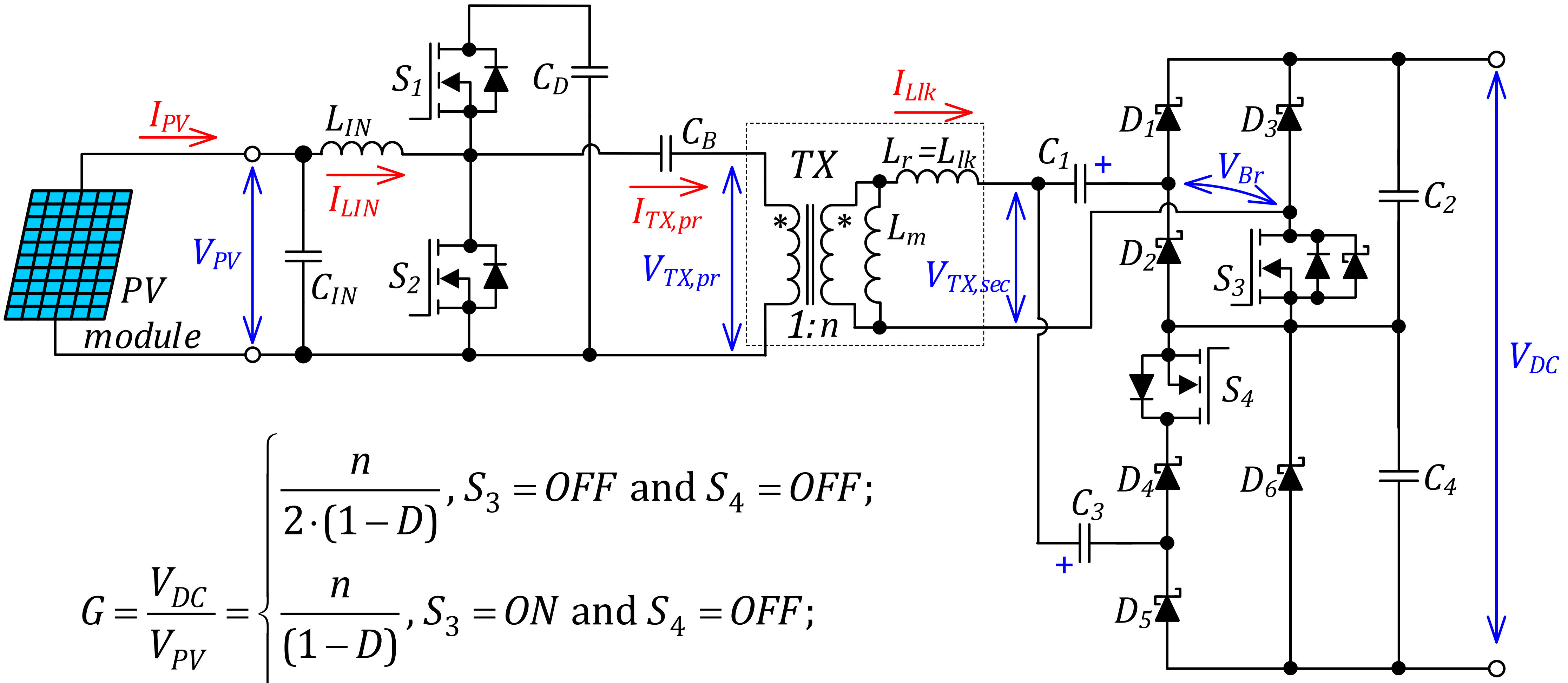


Challenges:

- *1:20 input range*
- *Health monitoring*
- *Partial shading*
- *Efficiency*

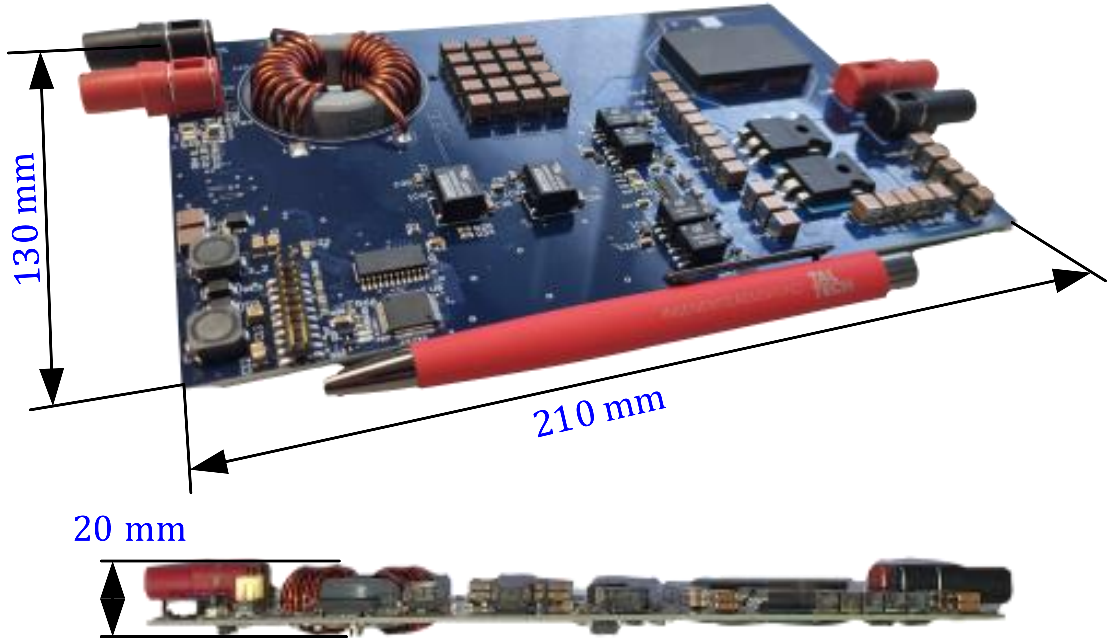
TAL TECH

CONVERTER - BOOST HALF-BRIDGE + 3-MODE RECT.



$$G = \frac{V_{DC}}{V_{PV}} = \begin{cases} \dfrac{n}{2\cdot(1-D)}, S_3 = OFF \text{ and } S_4 = OFF; \\ \dfrac{n}{(1-D)}, S_3 = ON \text{ and } S_4 = OFF; \\ \dfrac{2\cdot n}{(1-D)}, S_3 = ON \text{ and } S_4 = ON. \end{cases}$$

UNIPV2µG – UNIversal PhotoVoltaic to (2) µGgrid Interface



Features:

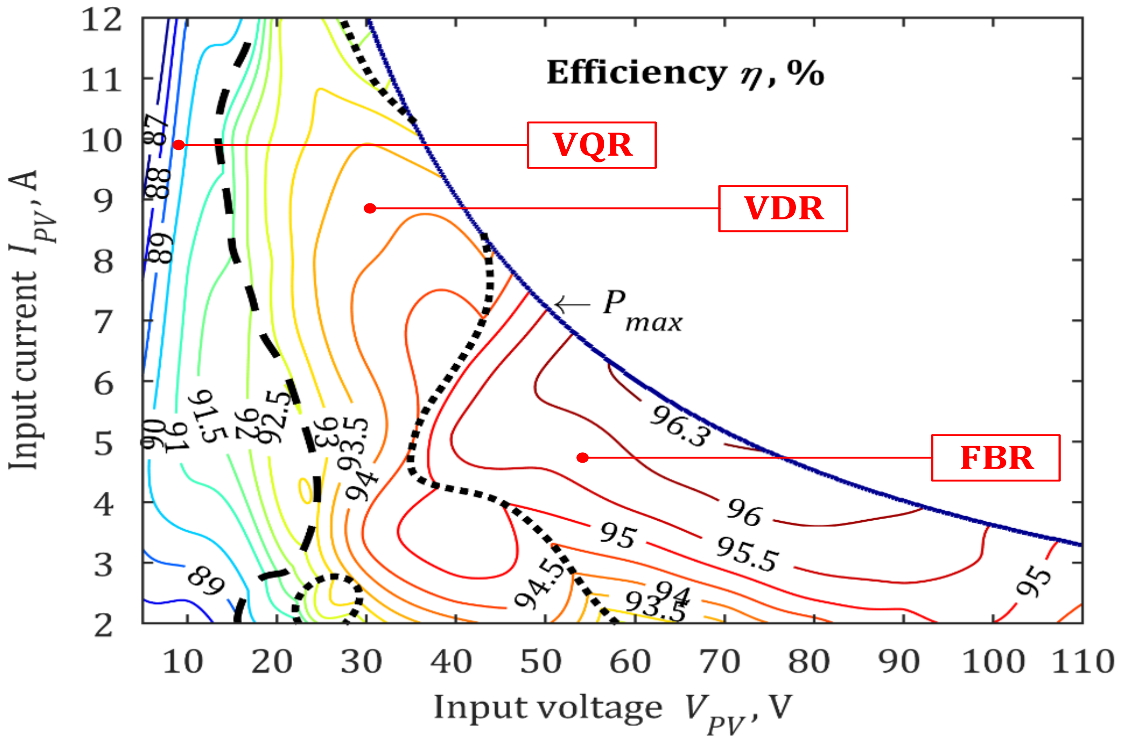
- *1-stage with input voltage range of 5..110V*
- *Duty cycle constrained to optimal range*
- *High linearity of $D(V_{PV})$ curves – feed-forward control*

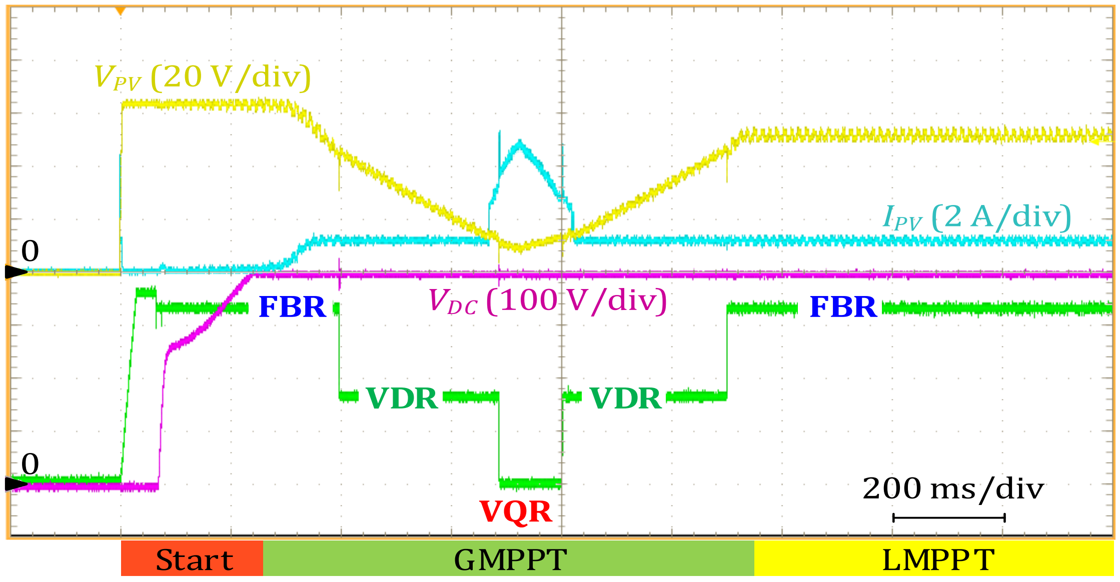
Component	Value/Type
Passive components	
Input inductor L_{IN}	90 µH
Input cap. C_{IN}	22 µF
Dc blocking cap. C_B	2 × 6.8 µF
Dc-link capacitor C_D	47 µF
Capacitors C_1, C_3	0.47 µF
Capacitors C_2, C_4	3 µF
Turns ratio n	6.3
Leakage ind. L_{lk}	10 µH
Magnetizing ind. L_m	1000 µH
Semiconductors	
Switches S_1 and S_2	IPB117N20NFD: Si / 12 mΩ / 200 V
Switch S_3	IPW60R180P7: Si / 180 mΩ / 650 V
Switch S_4	SCH2080KE: SiC / 80 mΩ / 1200 V
Driving of S_1…S_3	ADuM3223: 0 V / +9 V
Driving of S_4	ADuM3223: -5 V / +19 V
Diodes D_1…D_6	CSD01060: SiC/2 A/600 V

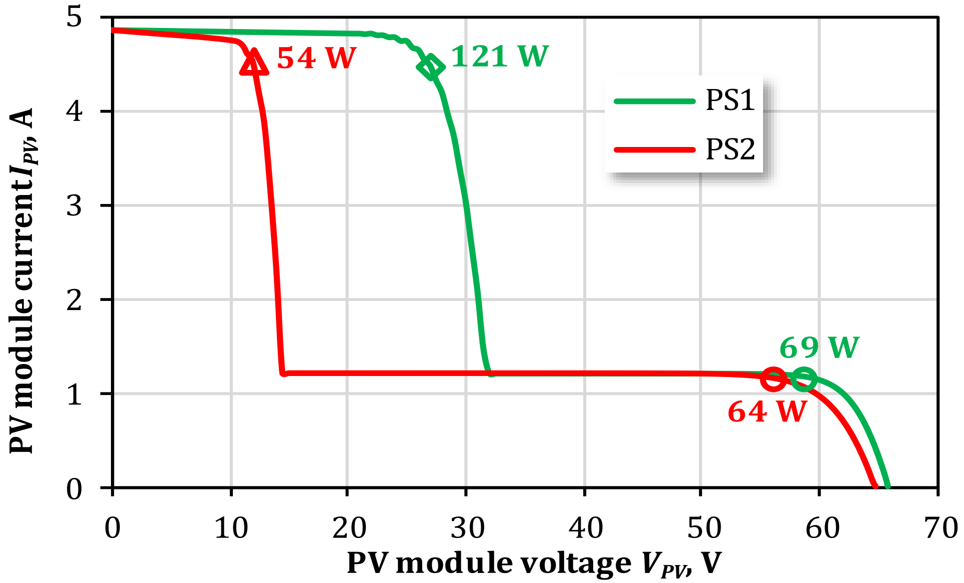
A. Chub, D. Vinnikov, O. Korkh, M. Malinowski and S. Kouro, "Ultrawide Voltage Gain Range Microconverter for Integration of Silicon and Thin-Film Photovoltaic Modules in DC Microgrids," in IEEE Transactions on Power Electronics, vol. 36, no. 12, pp. 13763-13778, Dec. 2021, doi: 10.1109/TPEL.2021.3084918.

PERFORMANCE

- ***Efficiency:*** *Up to 96.3% - more than any other before*
- ***Global MPPT:*** *Maximum energy harvest in any conditions*
- ***Fast scanning:*** *high controllability and maximized harvest*
- ***Compatibility:*** *nearly any PV module on the market, regardless of technology*







TAL TECH

FLEXIVERTER

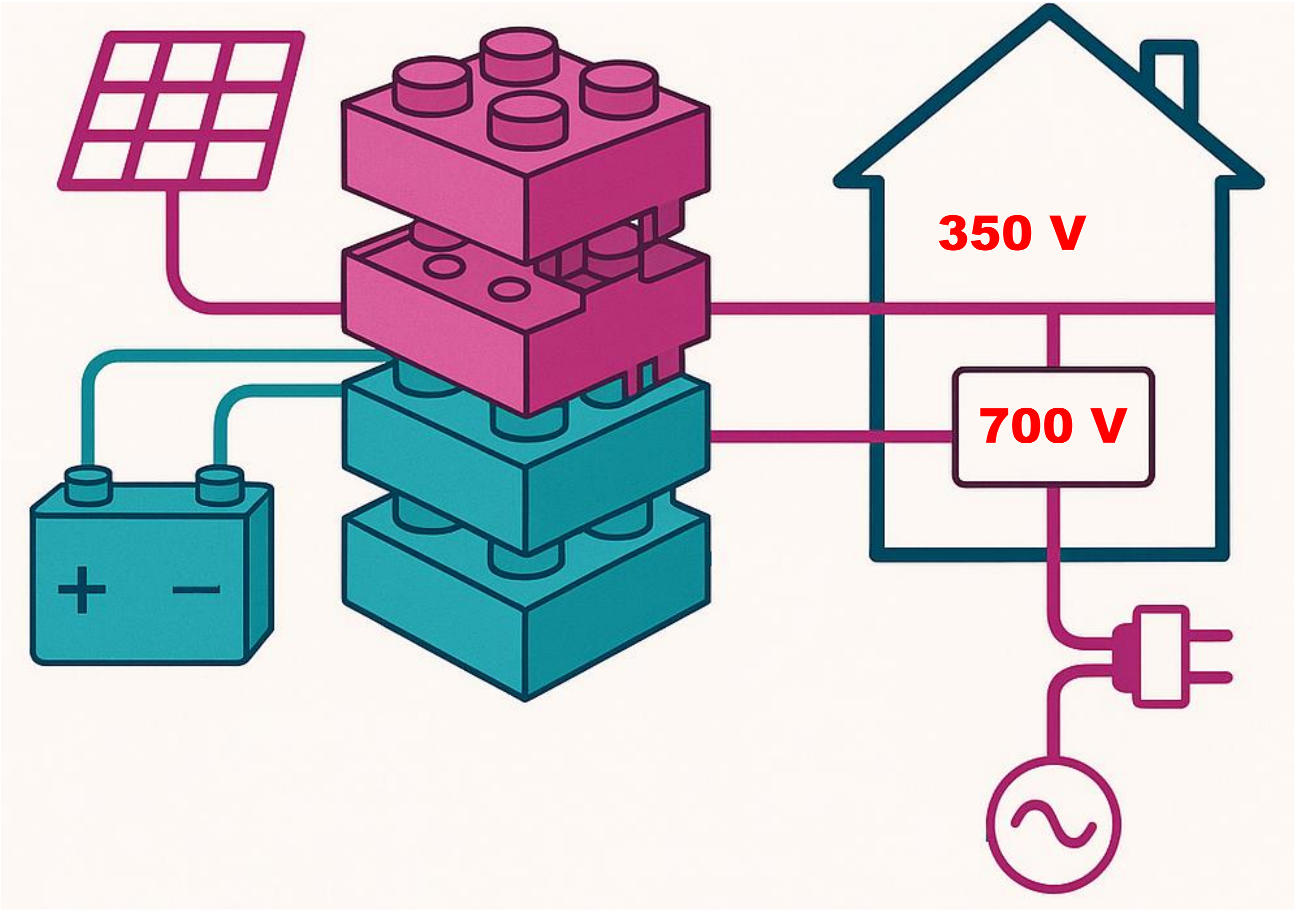
FLEXIBLE CONVERTER

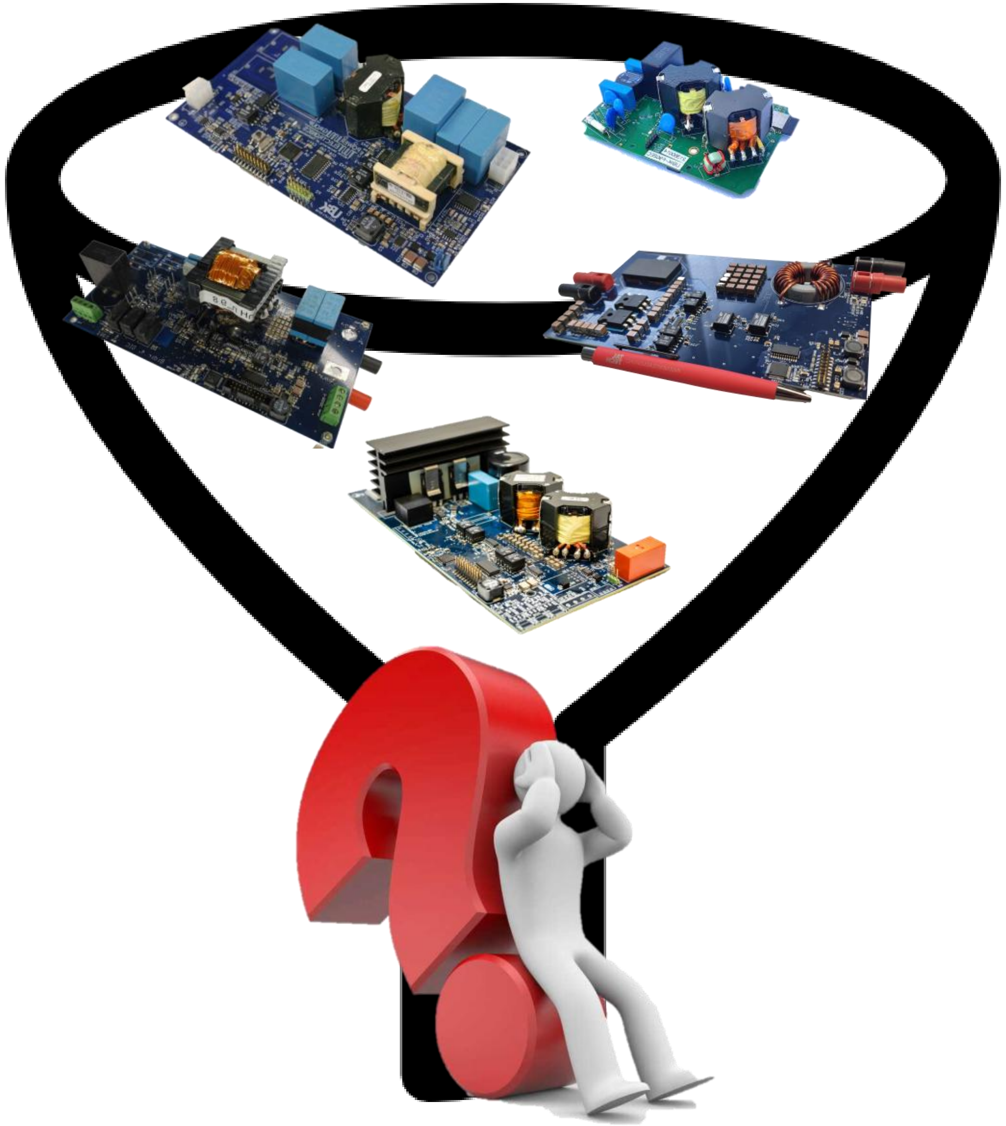
FOR NANOPRODUCERS AND STORAGE (<800W)

RESIDENTIAL APPLICATIONS

doi:10.3390/en12061080

WHY UNIVERSAL IS NEEDED?





FLEXIVERTER – FLEXIble conVERTER
power electronics “LEGO” for ZEB

Novel approach to the power electronic building block for the residential DC coupled power distribution systems. Characterized by the high versatility and ease of use, and features the embedded control, communication and auxiliary power systems


EUIPO
EUROPEAN UNION INTELLECTUAL PROPERTY OFFICE

Registreeritud / Registered 01/07/2020

No 018202165

EUROOPA LIIDU INTELLEKTUAALOMANDI AMET
REGISTREERIMISTUNNISTUS

Käesolev registreerimistunnistus väljastatakse allpool esitatud Euroopa Liidu kaubamärgile. Euroopa Liidu kaubamärkide registrisse on tehtud vastavad kanded.

EUROPEAN UNION INTELLECTUAL PROPERTY OFFICE
CERTIFICATE OF REGISTRATION

This Certificate of Registration is hereby issued for the European Union trade mark identified below. The corresponding entries have been recorded in the Register of European Union trade marks.

FlexiVerter

Tegevdirektor / The Executive Director

Christian Archambeau

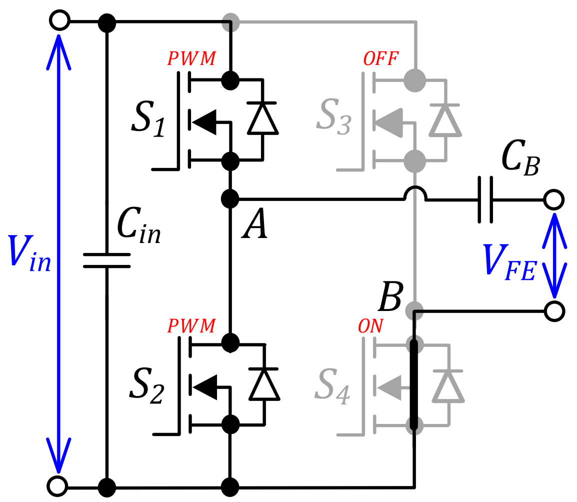
www.euipo.europa.eu

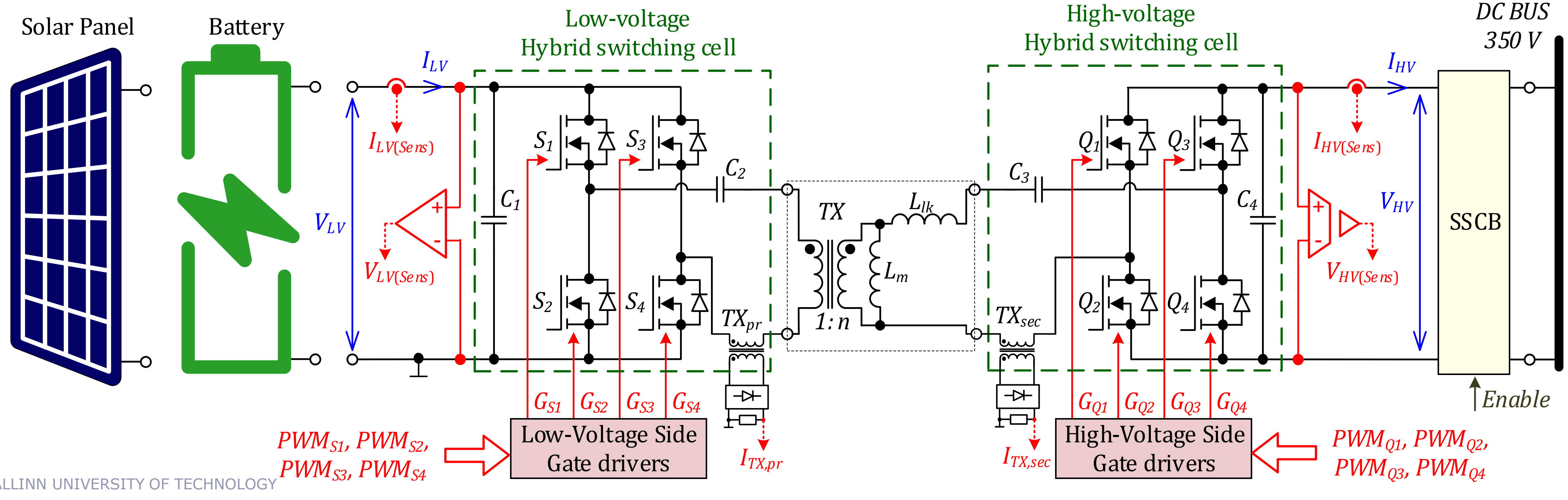
- *Aimed at nano-producers (easy online permit in Estonia, <800W)*
- *Can operate with any residential PV module and 24V or 48V BESS*
- *Compatible with both 350±30V and 700±60V microgrids*
- *Supports the droop control functionality and features the integrated solid state protection*

SERIAL RESONANT BUCK-BOOST DUAL ACTIVE BRIDGE

- *Ultra-wide input/output voltage and load regulation range enabled by* ***Topology Morphing Control***
- *Soft transition between topology configurations are achievable*
- *Experimental efficiency reaching* ***98%*** *in both directions of power flow*
- *BOM optimized – embedded protection and integrated magnetics*

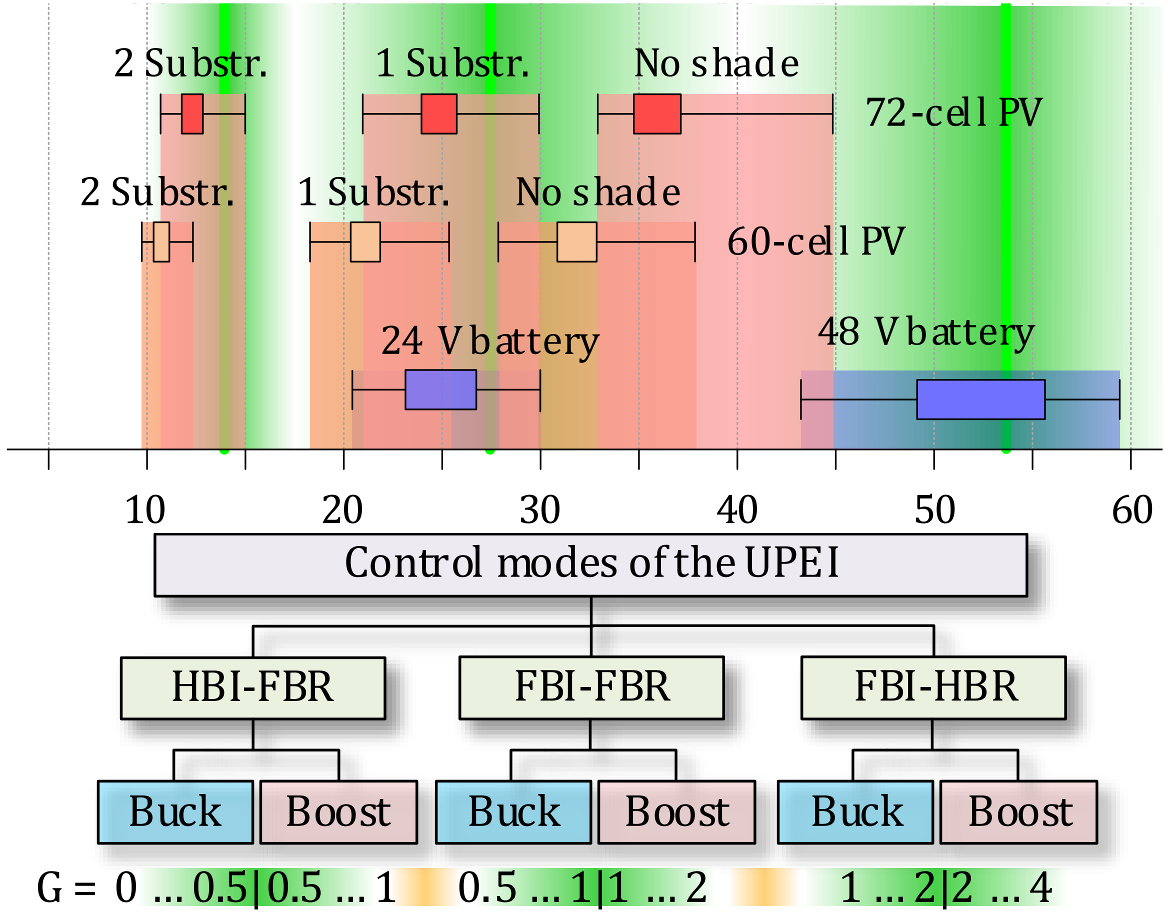
FB/HB reconfiguration

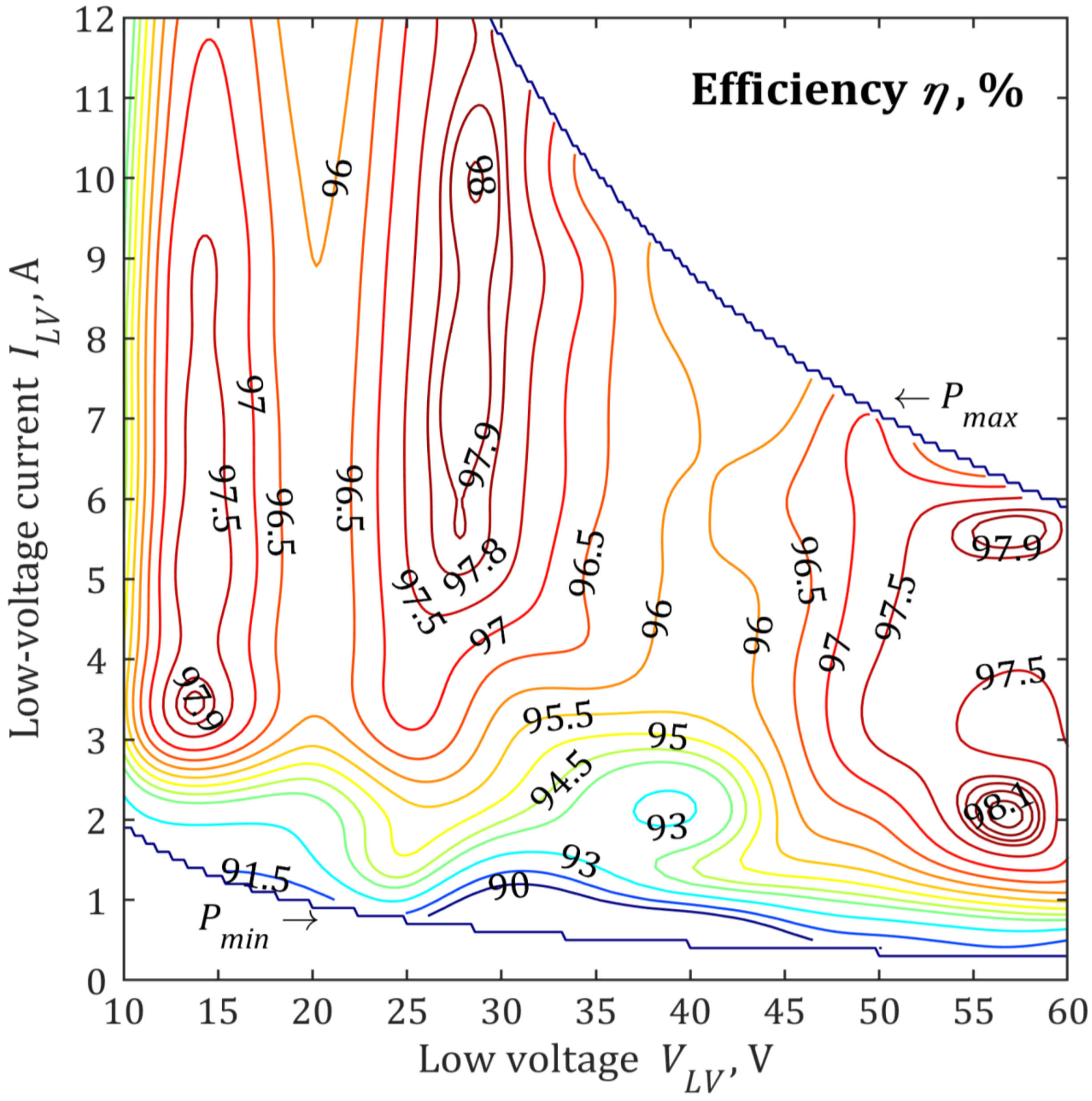




PERFORMANCE

- *Input range of 10..60V is compatible with common PV modules (incl. partial shading) and 24/48V batteries*
- *Six operating modes utilized to achieve wide range*
- *Three distinct efficiency peaks – allow to match with the most probable operating points*

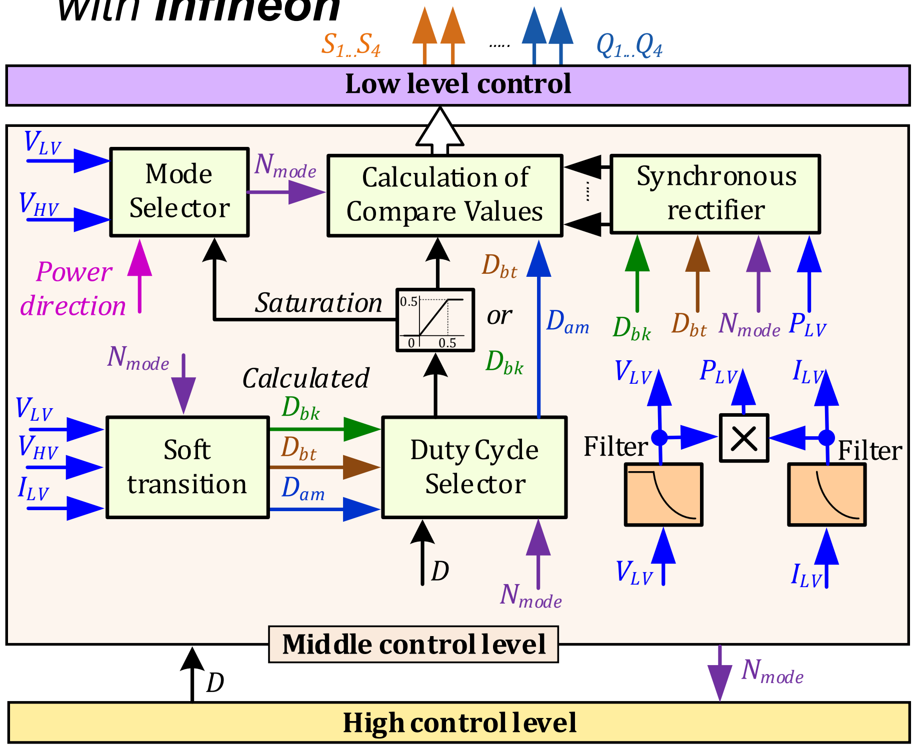


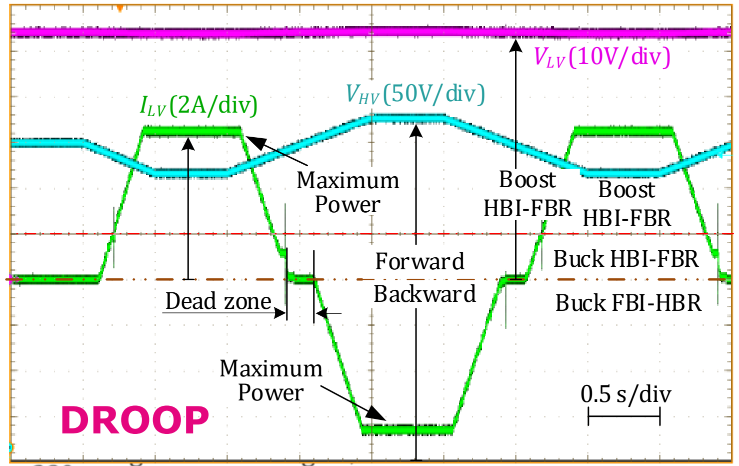


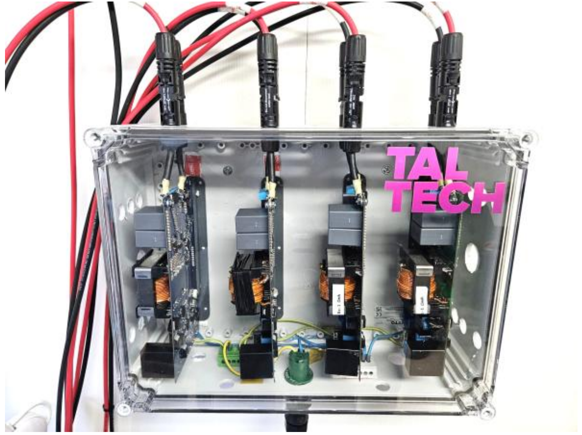
V. Sidorov, A. Chub and D. Vinnikov, "Bidirectional Isolated Hexamode DC–DC Converter," in IEEE Transactions on Power Electronics, vol. 37, no. 10, pp. 12264-12278, Oct. 2022, doi: 10.1109/TPEL.2022.3170229.

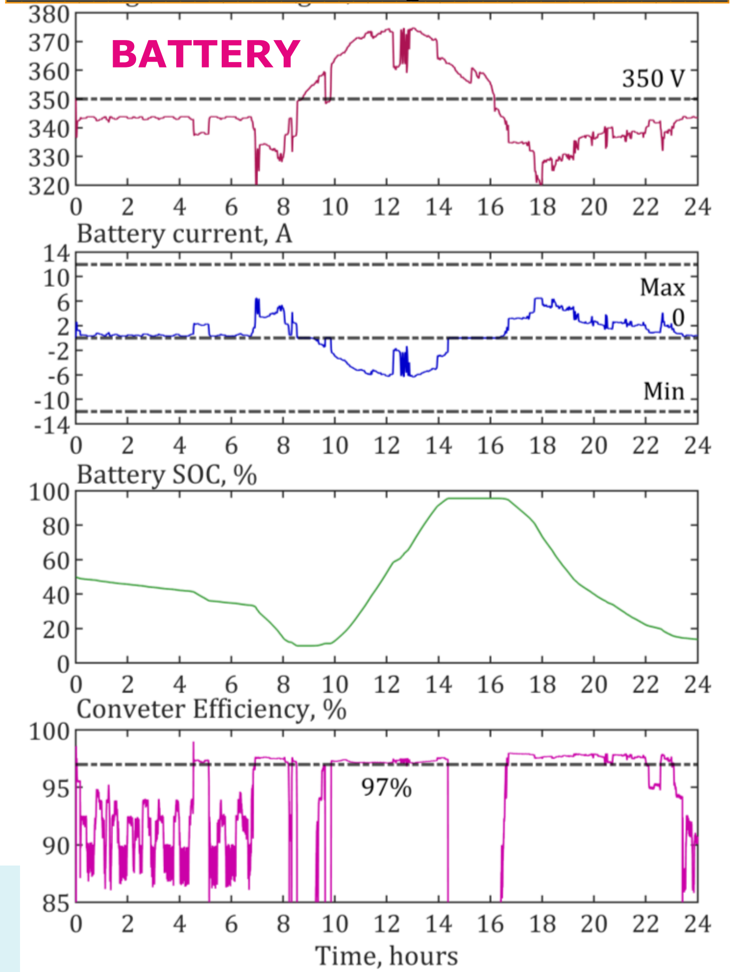
OPERATION IN DC MICROGRID

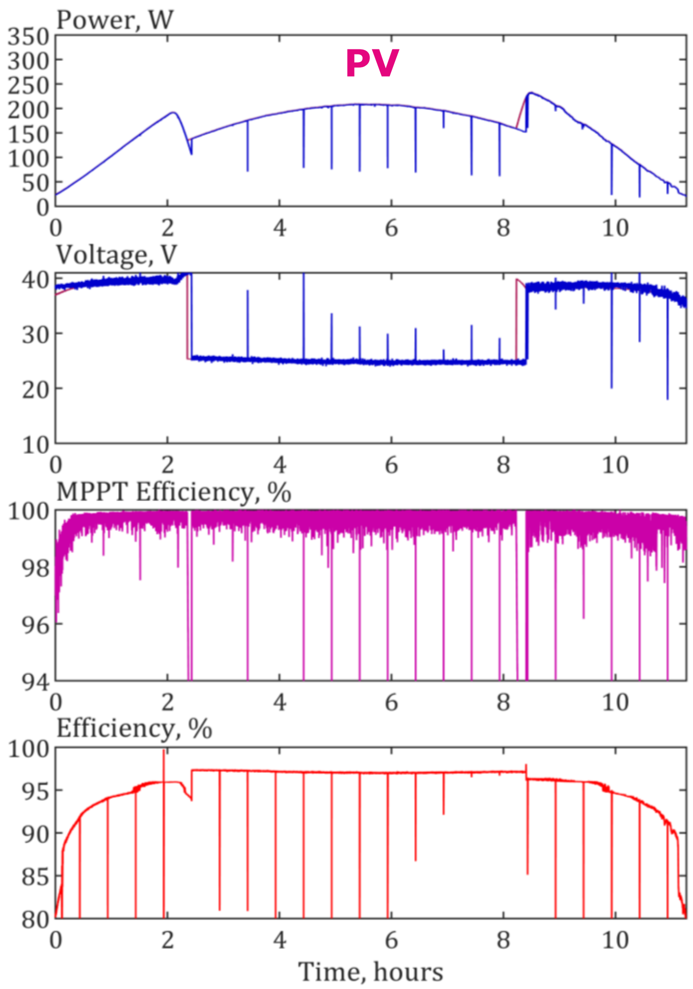
- *Input source type identification*
- *DC droop + Global MPPT*
- *Battery soft-start and safe operation*
- *Ongoing work: device miniaturization with **Infineon***





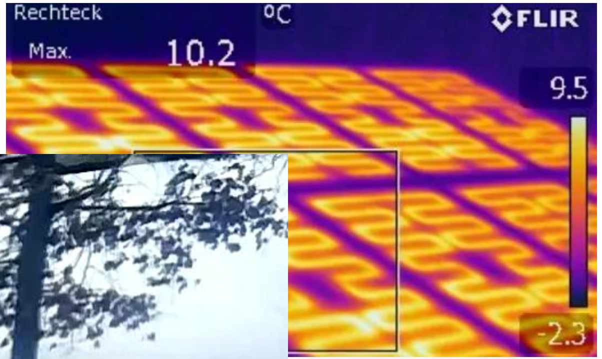


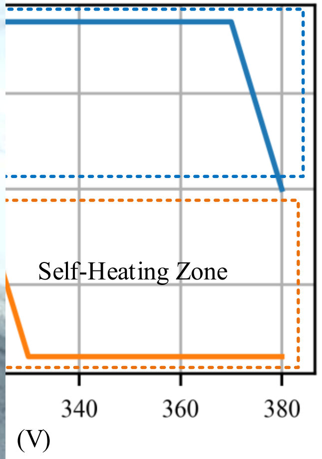


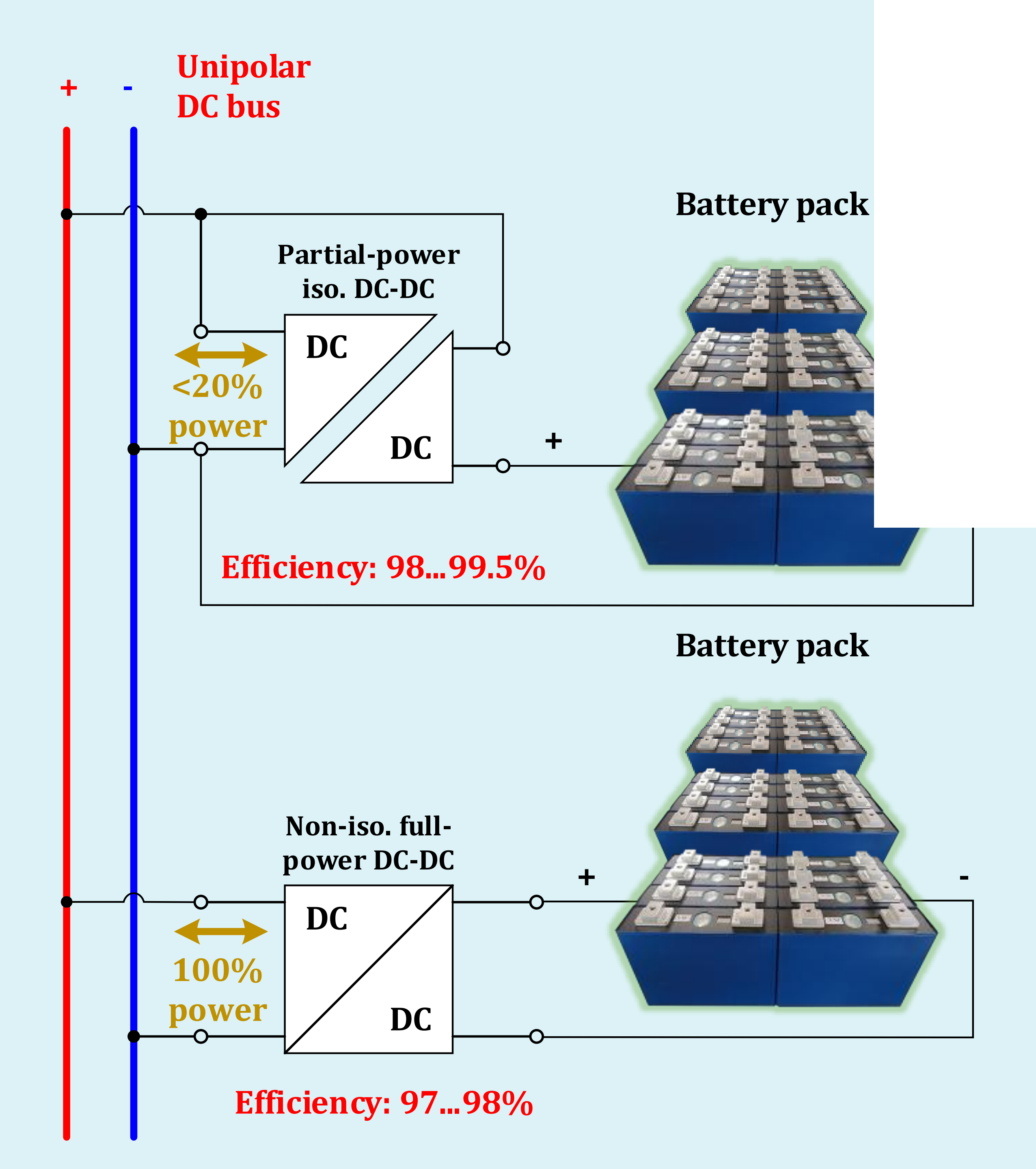


V. Sidorov, A. Chub, D. Vinnikov and A. Lindvest, "Novel Universal Power Electronic Interface for Integration of PV Modules and Battery Energy Storages in Residential DC Microgrids," in IEEE Access, vol. 11, pp. 30845-30858, 2023.

FLEXIVERTER® – NEW OPPORTUNITIES





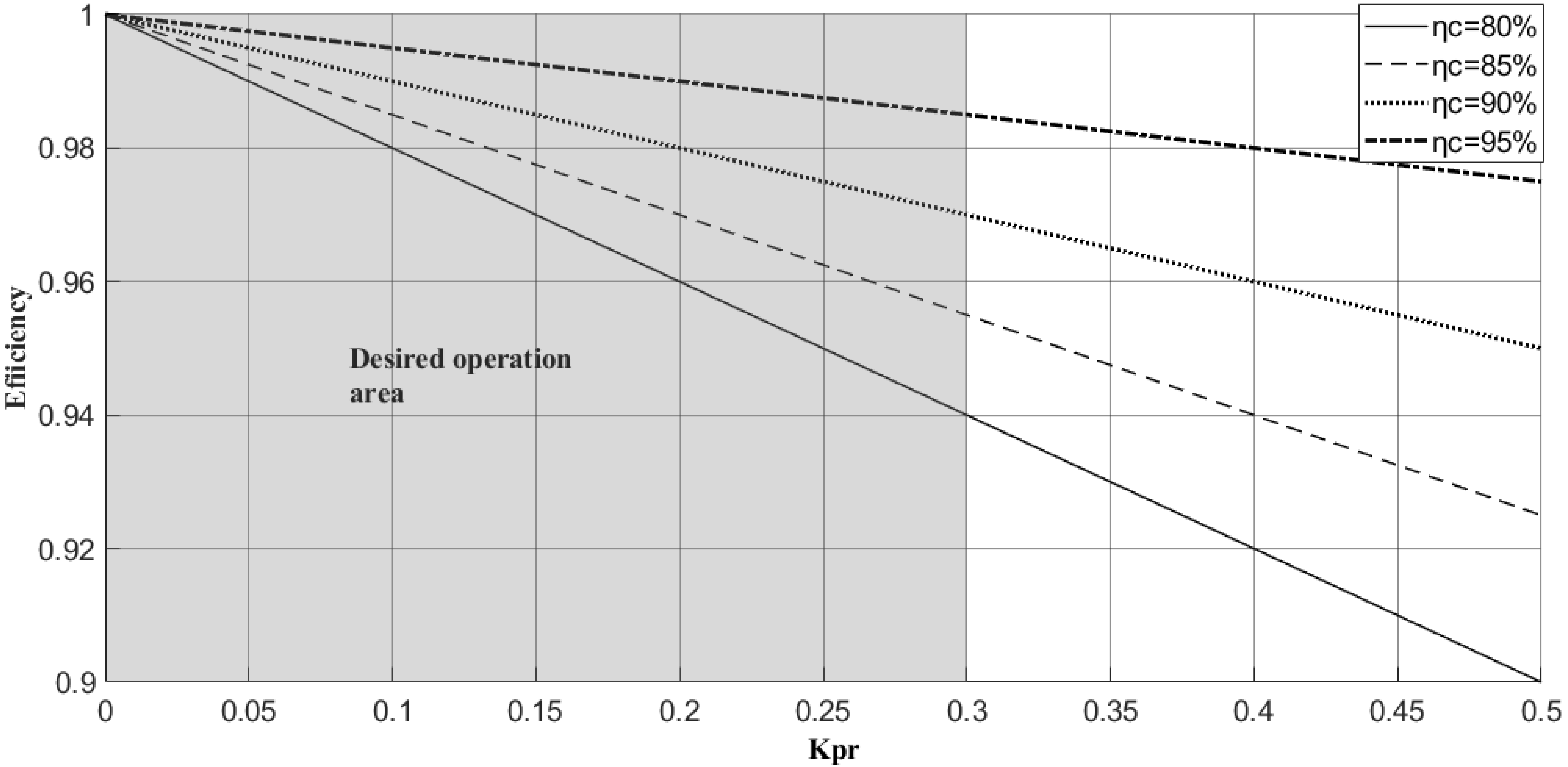


FORCE

FRACTIONAL POWER CONVERTERS

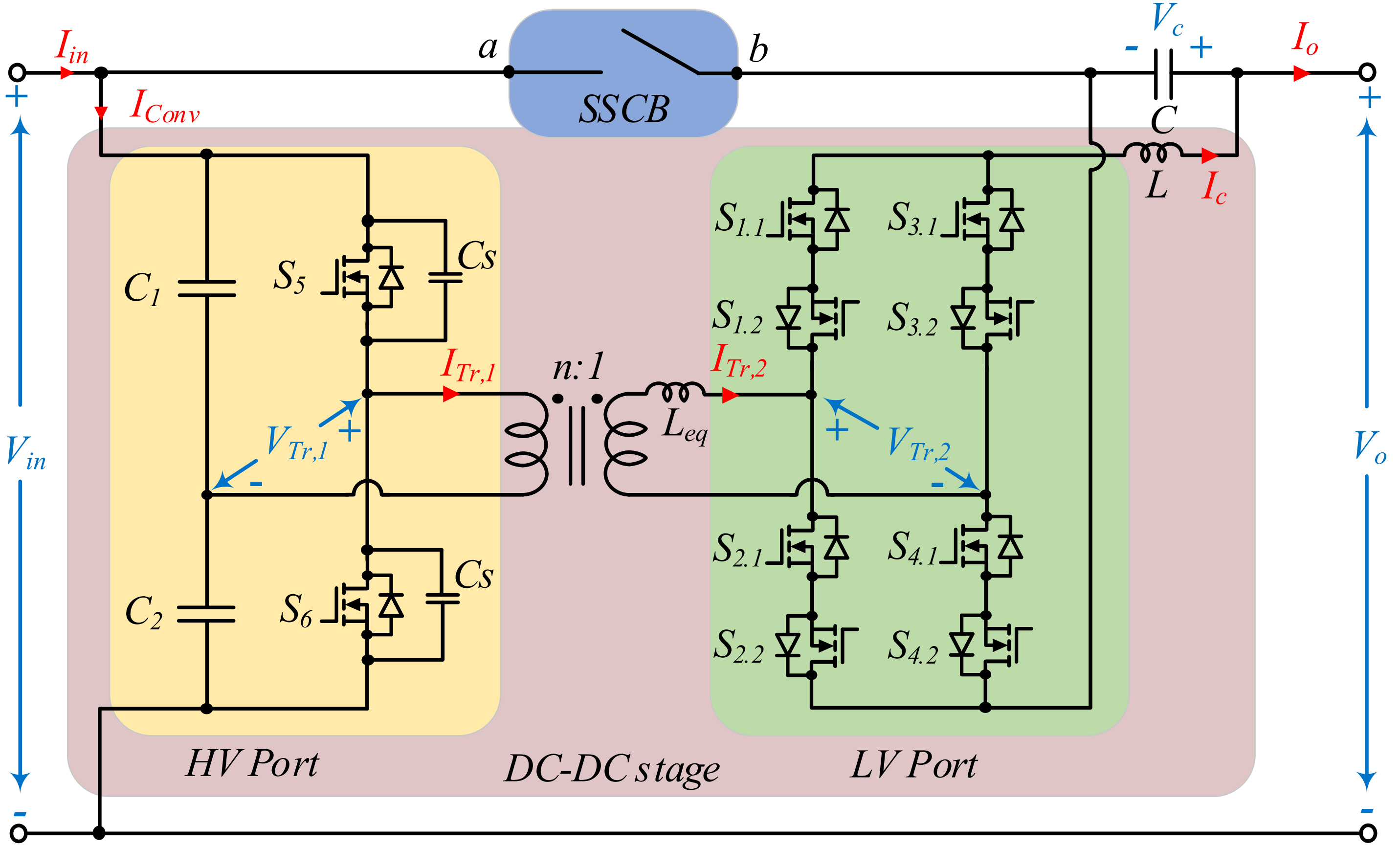
FOR HIGH VOLTAGE BATTERIES

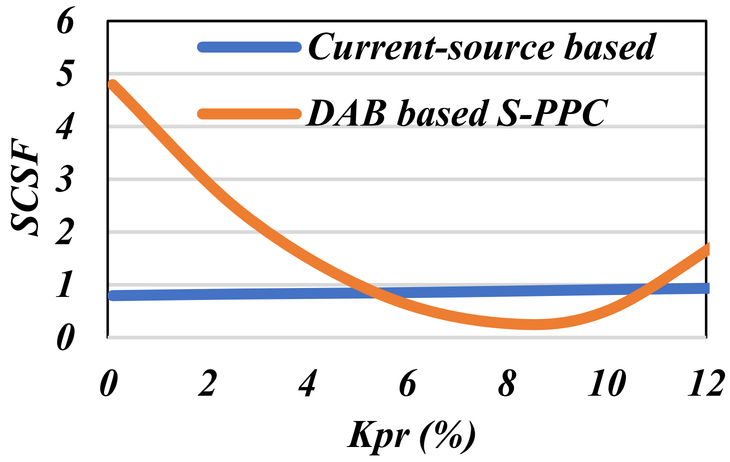
FRACTIONAL VS. FULL POWER

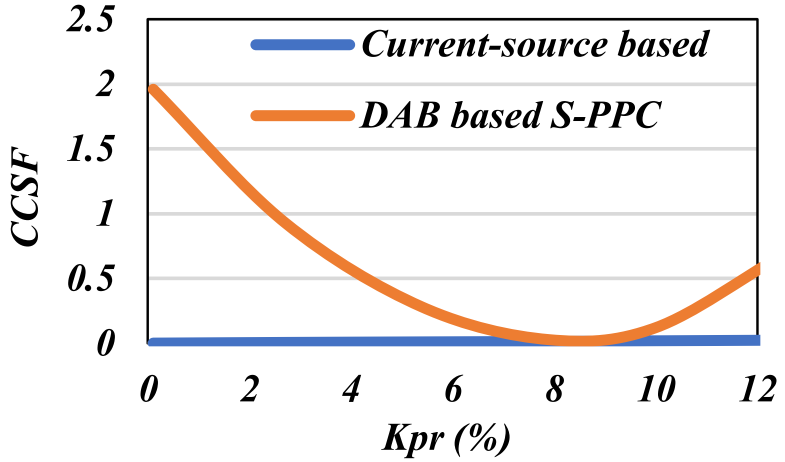


OUR SOLUTION

- ***Current-fed** implementation limits current stress on components*
- ***Step-up/down** architecture maximizes efficiency and power density*
- *Can manage **current control at zero series voltage***
- ***RMS** current of capacitor is **constrained***
- *Series port utilizes bidirectional switches for **4-quadrant operation** and full soft switching*
- *Half-bridge implementation improves efficiency of the isolation transformer*
- *Design can use **low-cost** semiconductors*

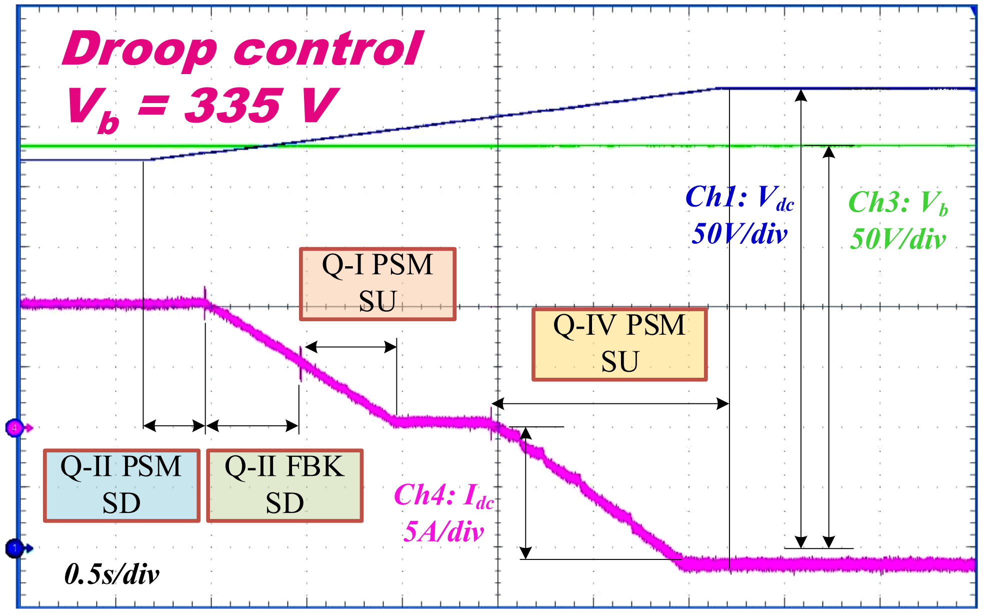


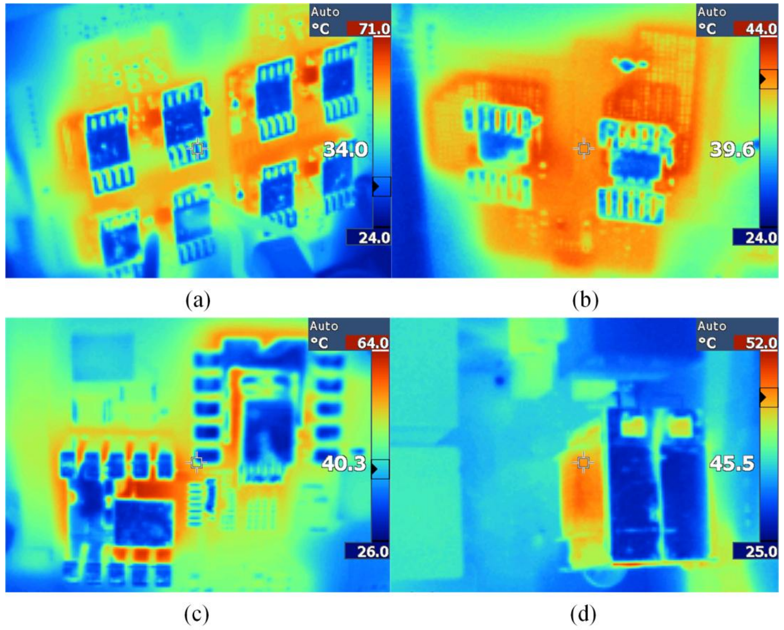


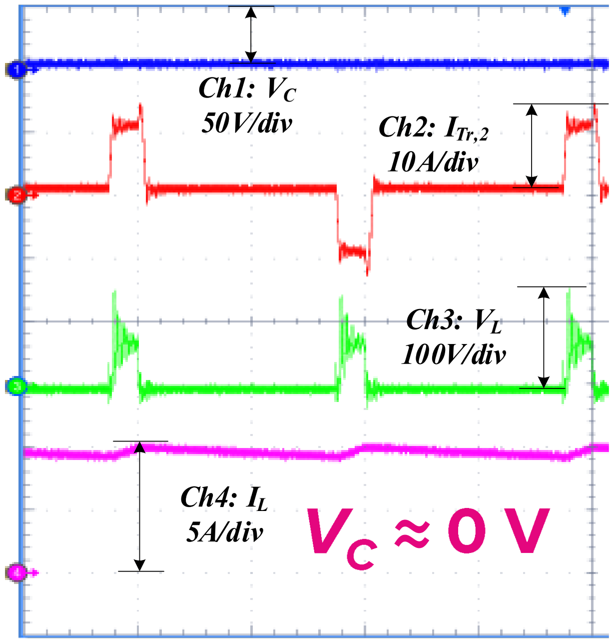


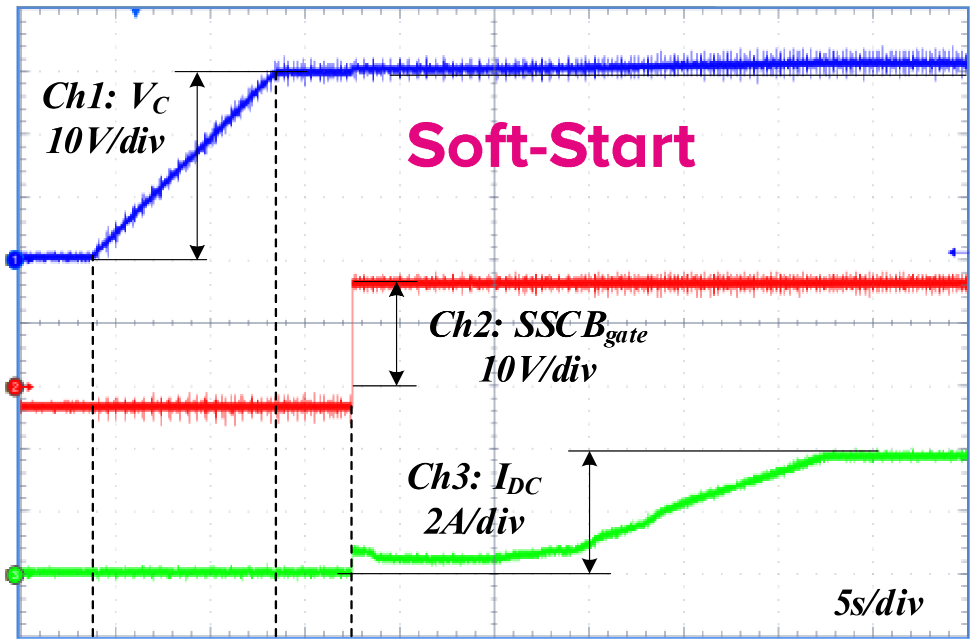
VALIDATION

- ***Topology morphing*** *control enables smooth transition between modes for* ***droop control***
- ***PCB-soldered heatsinks*** *are sufficient for thermal management (SSCB is the hottest semiconductor part)*
- *Control considers* ***variations*** *in both DC and battery voltage*





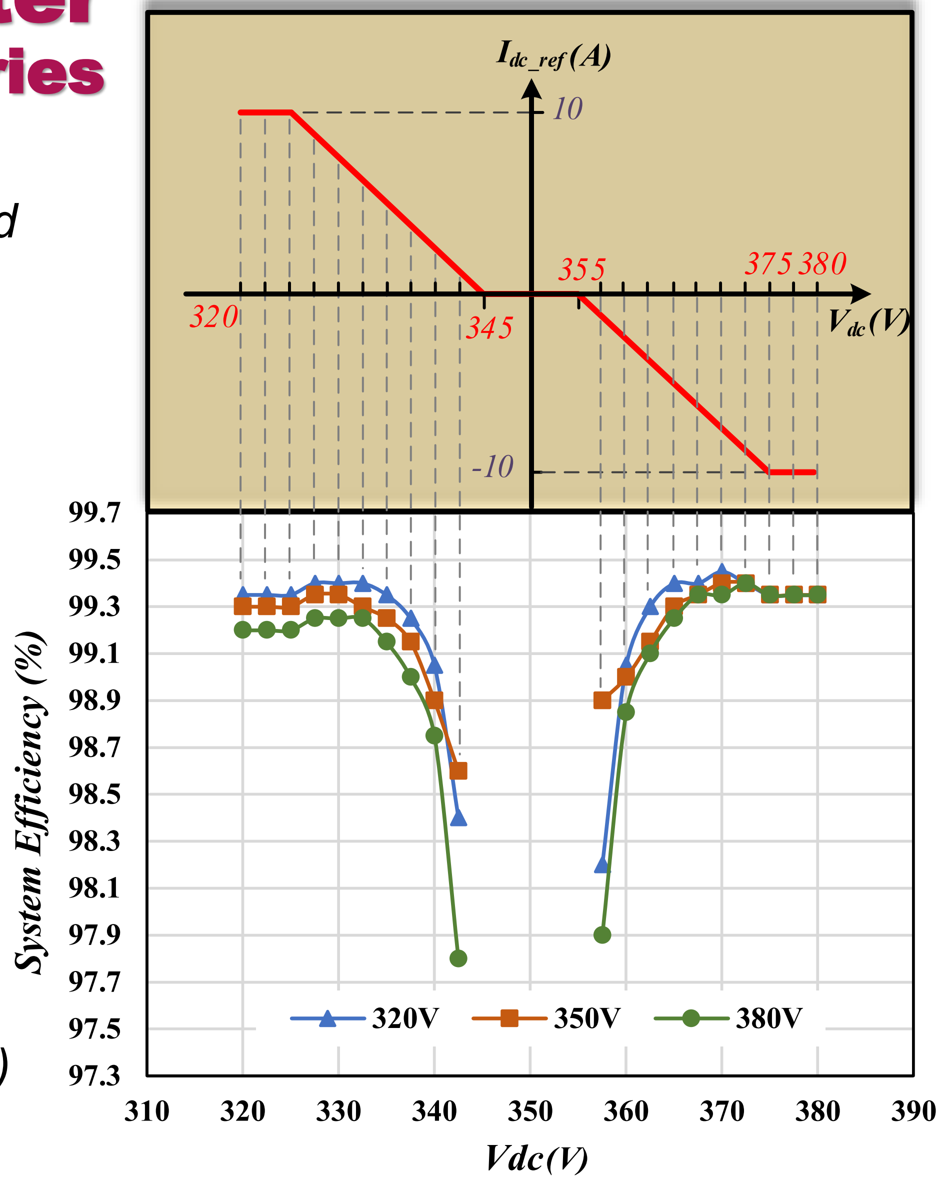




FORCE – Fractional pOweR ConvErter

For efficient integration of high-voltage batteries

- *Ultra-efficient – **over 99%** for 25%+ load*
- *Optimized for **350±30V** residential DC microgrids*
- *Designed for **second-life** LFP battery stack of 109 cells, approx. capacity ~8 kWh (depends on degradation)*
- ***Patented control** with soft-switching in the entire range*
- ***Soft-start** and embedded solid-state **protection** for compatibility with **CurrentOS** DC microgrid protocol*
- ***Low stress** on components*
- *Ready for emerging bidirectional **monolithic GaN switches** (by Infineon)*

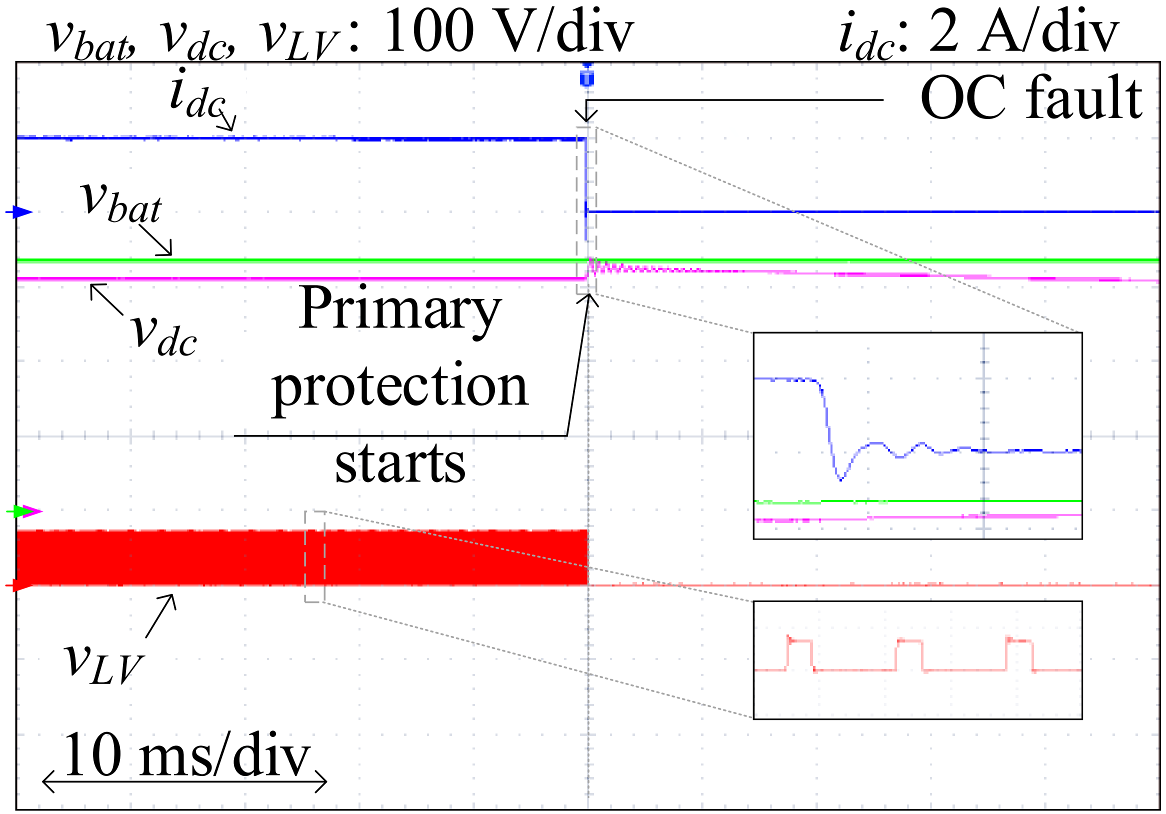


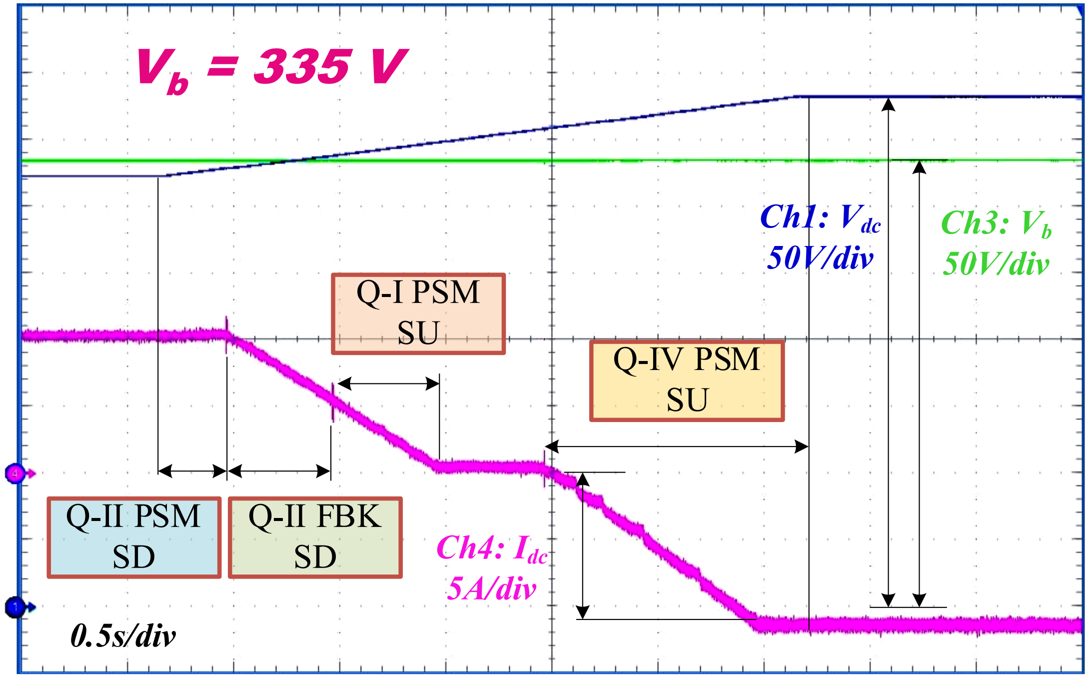
TAL TECH

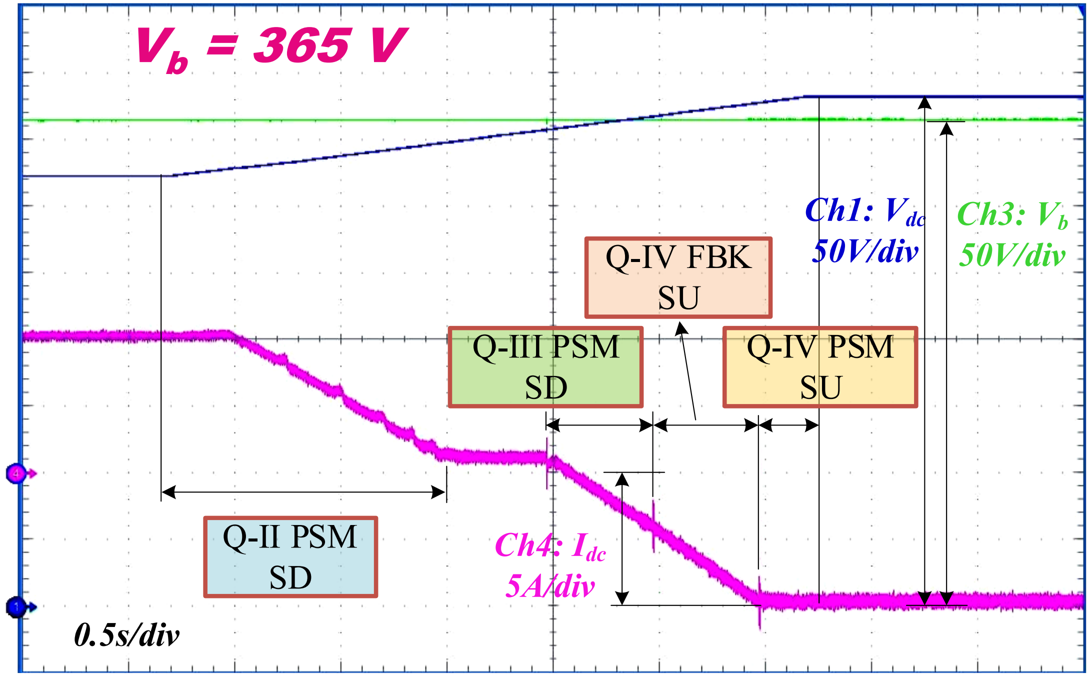
N. Hassanpour, A. Chub, N. Yadav, A. Blinov and D. Vinnikov, "High-Efficiency Partial Power Converter for Integration of Second-Life Battery Energy Storage Systems in DC Microgrids," in IEEE Open Journal of the Industrial Electronics Society, early access, doi: 10.1109/OJIES.2024.3389466

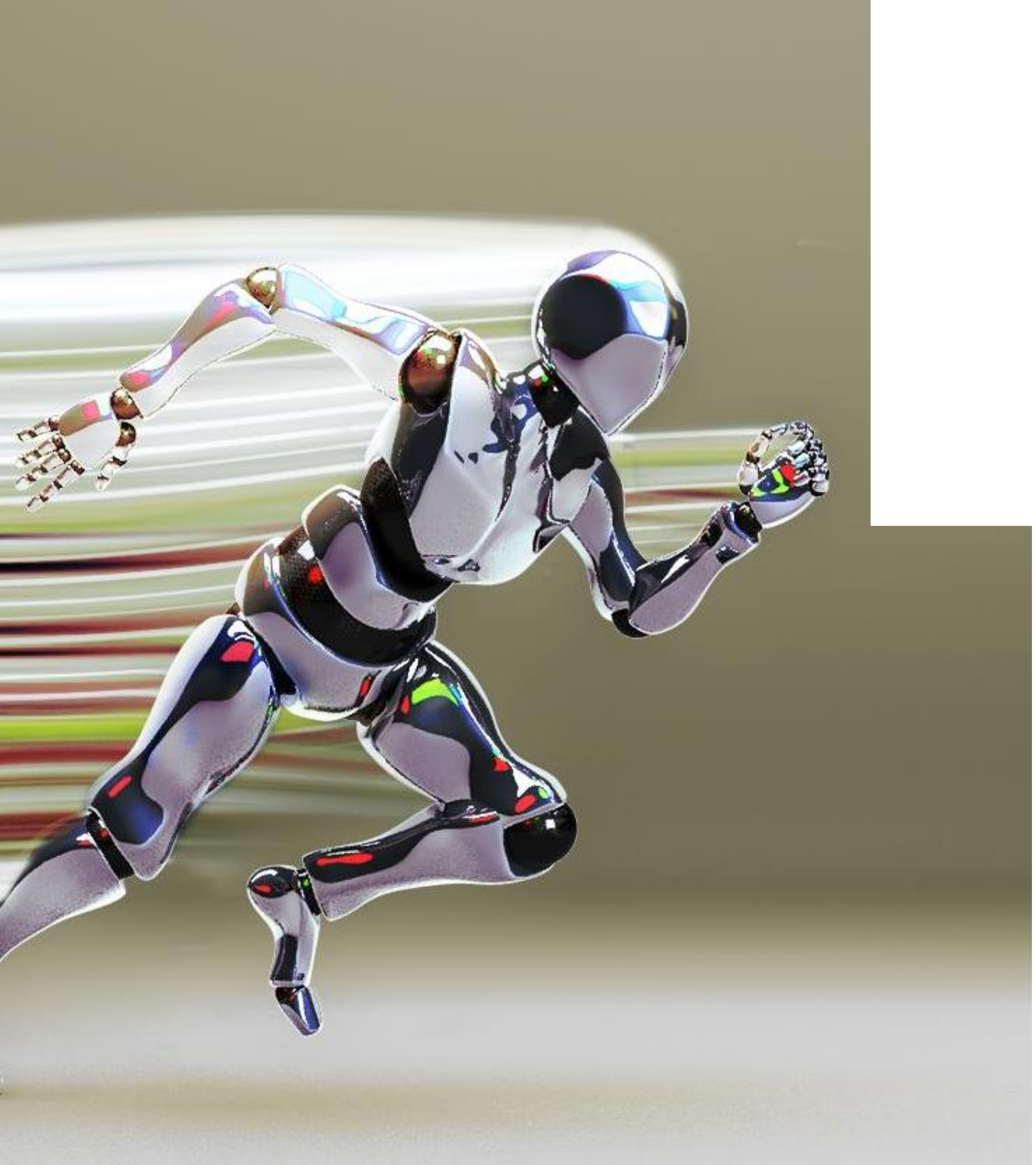
EXPERIMENTAL RESULTS

- *Topology morphing control enables smooth transition between modes*
- *PCB-soldered heatsinks are sufficient for thermal management (SSCB is the hottest part)*
- *Control considers variations in both DC and battery voltage*





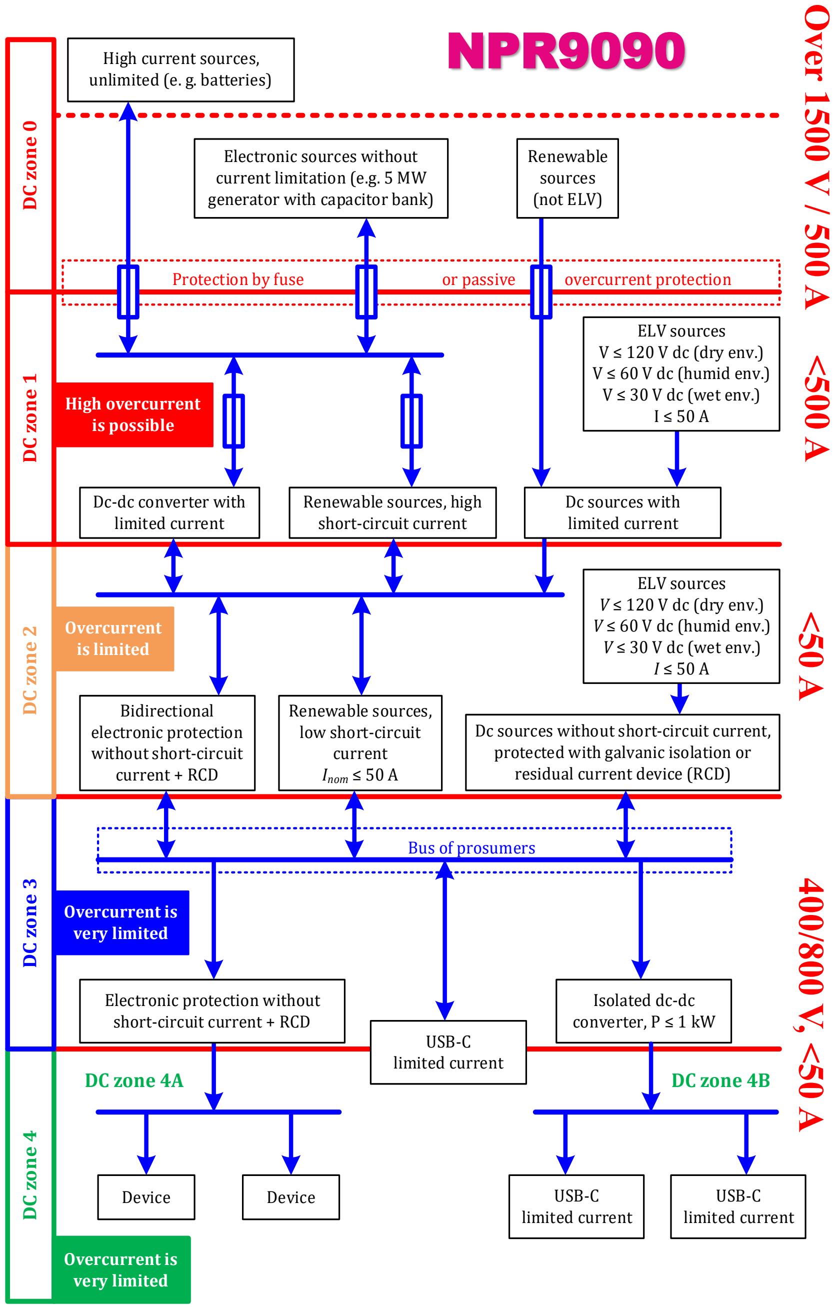


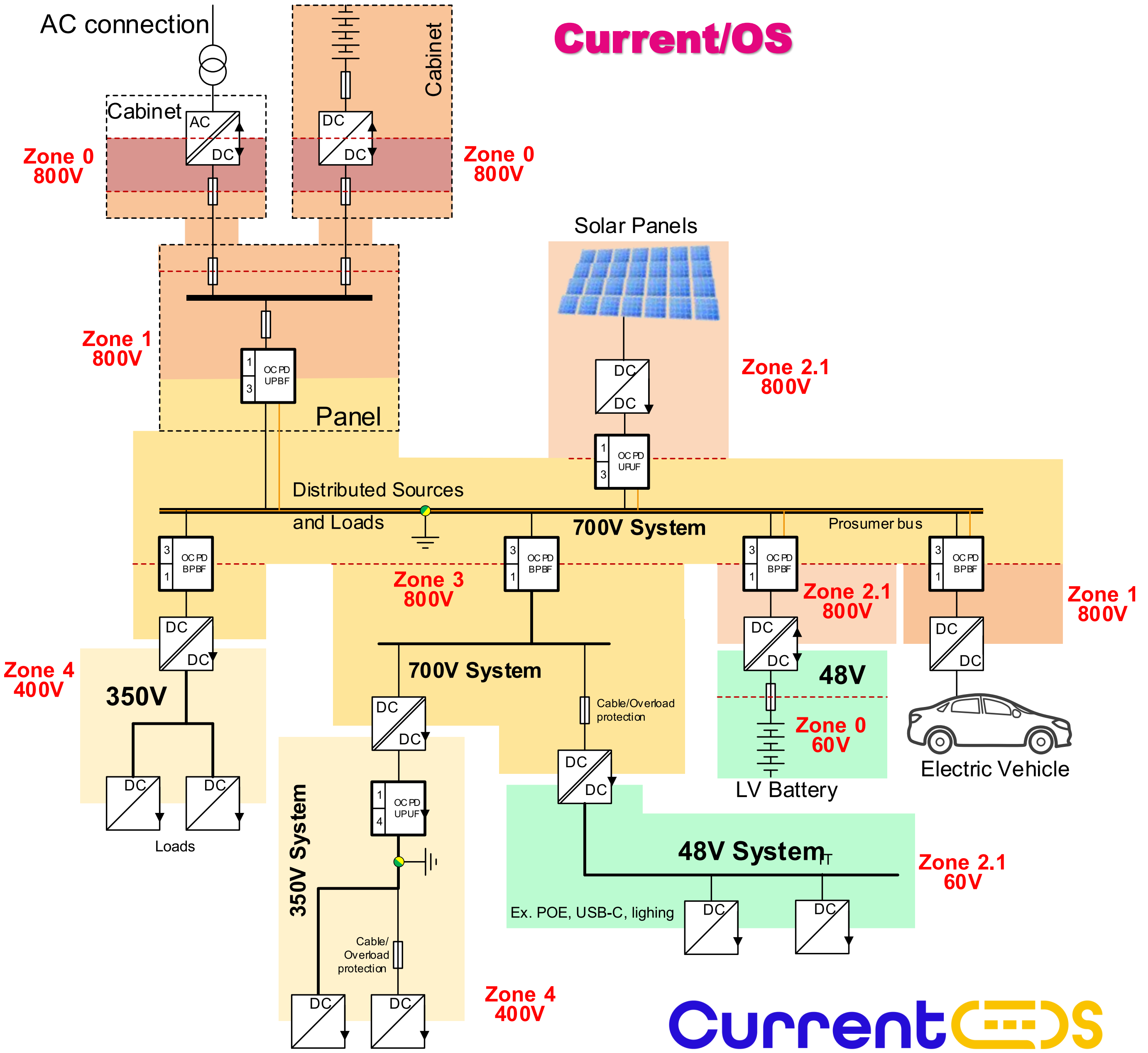


FAST DC PROTECTION

SOLID STATE SOLUTIONS

DC GRID CONCEPTS AND PROTECTION ZONES



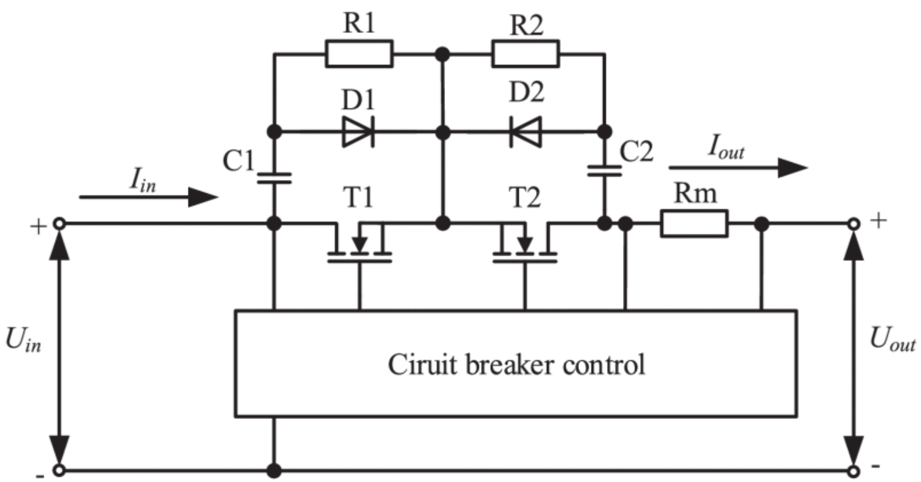


DESIGN REQUIREMENTS

- ***Current/OS*** *require DC Circuit Breakers faster than 50 ms used in protection* ***Zone 2.1*** *(energy stored limited to 600 J) and* ***Zone 1*** *(not limited stored energy), which would typically imply electromechanical technology for high currents*
- ***Current/OS*** *require DC Circuit Breakers faster than 1 ms used in protection* ***Zone 2.2****, which would typically imply hybrid technology for high currents*
- ***Current/OS*** *require DC Circuit Breakers faster than 10 μs used in protection* ***Zone 3****, which implies use of solid-state circuit breakers (SSCBs)*
- *In* ***Zone 3****, RCD are mandatory when the circuit includes socket outlets*
- *SSCBs are very sensitive, which implies limits* ***on current ramp-rate*** *for device hot swap.*
- *SSCBs could be* ***cost-sensitive*** *as they require high semiconductor area to provide low losses*

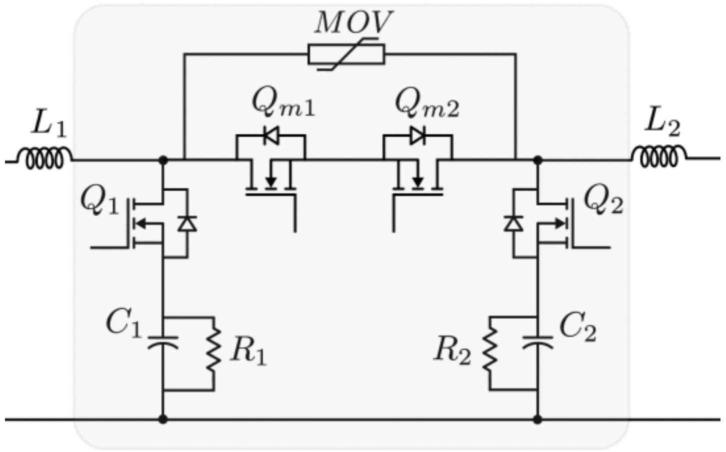
OUR CONCEPTS

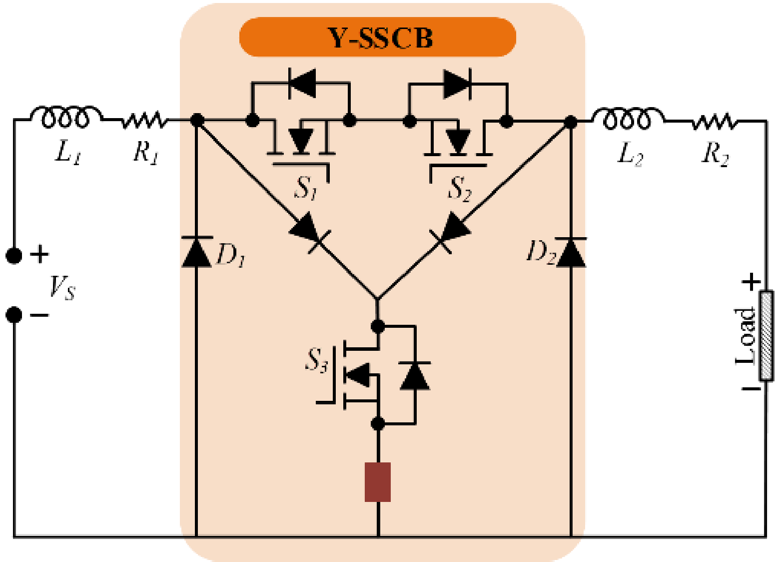
Simplest/Cheapest



T. Jalakas, S. N. Banavath, A. Chub, I. Roasto and D. Vinnikov, "Performance Analysis of Protection Methods in Residential DC Microgrids," 2023 IEEE 17th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Tallinn, Estonia, 2023, pp. 1-6, doi: 10.1109/CPE-POWERENG58103.2023.10227388.

Advanced SSCBs with reduced stress on components (but more expensive)



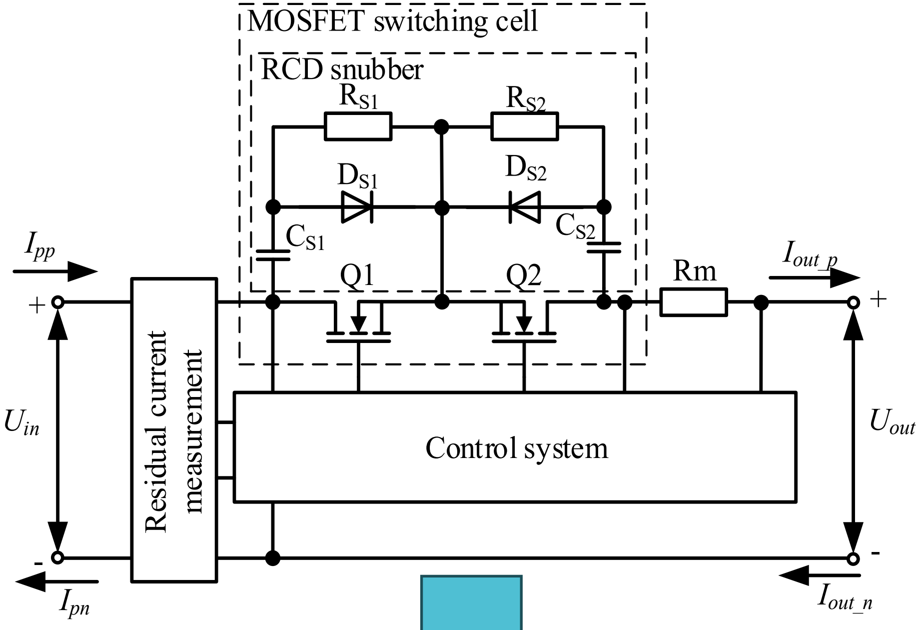


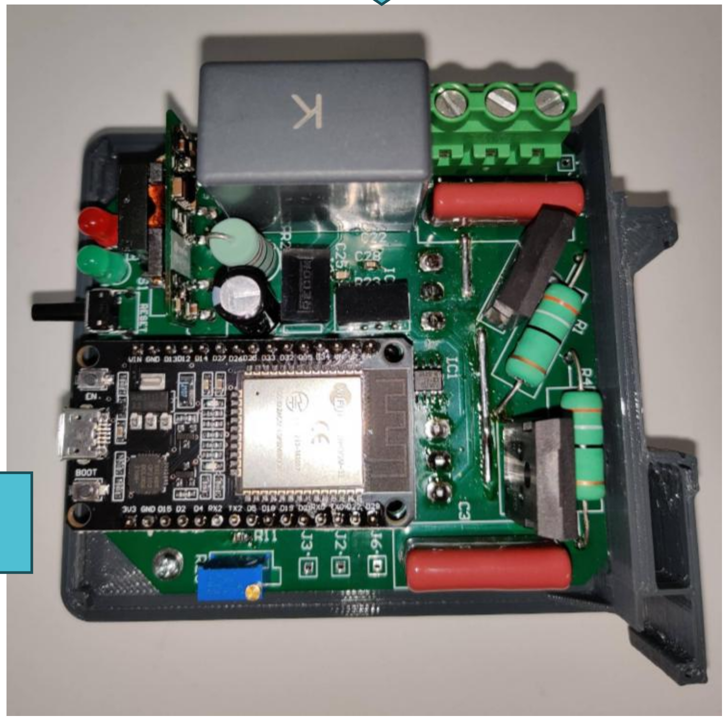
P. Aditya, S. N. Banavath, A. Lidozzi, A. Chub and D. Vinnikov, "Bidirectional SSCB for Residential DC Microgrids with Reduced Voltage and Current Stress during Fault Interruption," 2023 IEEE 17th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Tallinn, Estonia, 2023, pp. 1-6, doi: 10.1109/CPE-POWERENG58103.2023.10227379.

S. Rahimpour, O. Husev and D. Vinnikov, "A Family of Bidirectional Solid-State Circuit Breakers With Increased Safety in DC Microgrids," in IEEE Transactions on Industrial Electronics, early access, doi: 10.1109/TIE.2023.3337493.

SAFEBREAK – SAfe and Fast DC Electronic BREAKer

- Utilizes SiC JFETs for **low R_{DSon}**
- Contains **residual current sensor** for ultimate safety
- **Fast speed** – short circuit detected within 10 µs (safer for user too)
- **Future work:** MQTT smart connection to **Energy Management System**

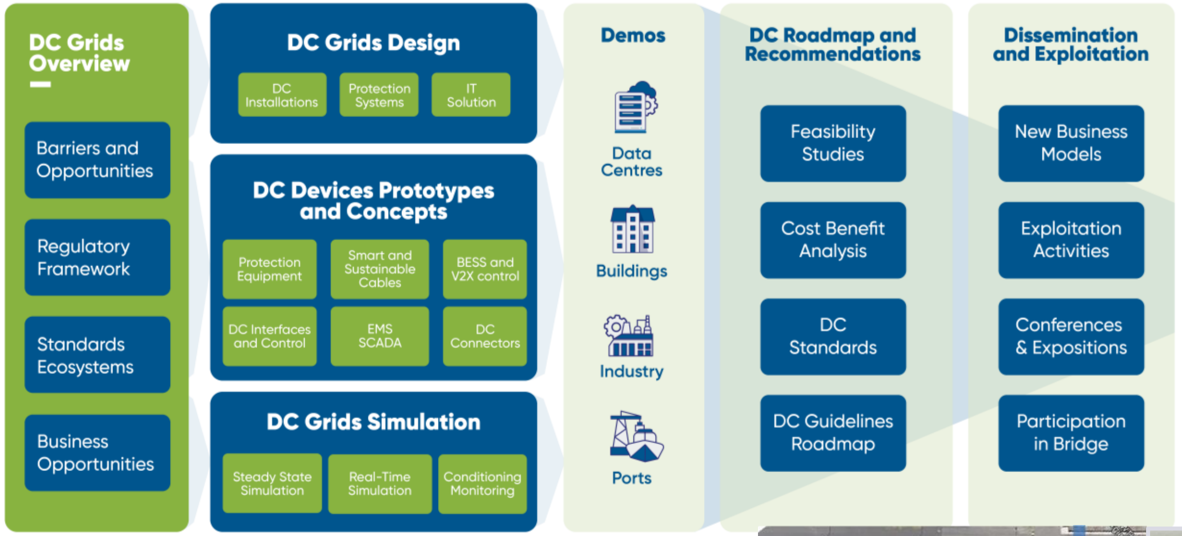




SHIFT2DC – EU PROJECT PUSHING DC TECHNOLOGY

- ***Key figures:*** *21 partners + 6 affiliates, 11 M€, 13 countries, 4 demos*
- ***Key objectives:*** *15+ industry solutions, tools for sizing and design, comprehensive tutorial-style deliverables on standardization/protection/modeling, droop control based energy management, etc.*
- ***Main targets/demos:*** ***DC*** *buildings,* ***DC*** *data centers,* ***DC*** *ports (digital twin), and* ***DC*** *industry*
- ***TalTech's role:*** *WP4 "Demos" leadership and development of 2 innovative DC-DC solutions*

Concept



Demos

PEMC 2026 IN TALLINN – SAVE THE DATE!

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CO-SPONSORED BY THE IEEE IES

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- *Highly relevant program on power electronics, controls, electrical drives, robotics and their industrial applications*
- *~150 papers to be presented*
- *Tutorials from world-renown experts: J.W. Kolar, M. Malinowski, F. Blaabjerg, A. Rathore, etc.*
- *12 IES SYPA awards at $1,500 USD each will be granted*
- *Entertaining social events for attendees, special events for students and WiE members*
- *Luncheons and coffee breaks*

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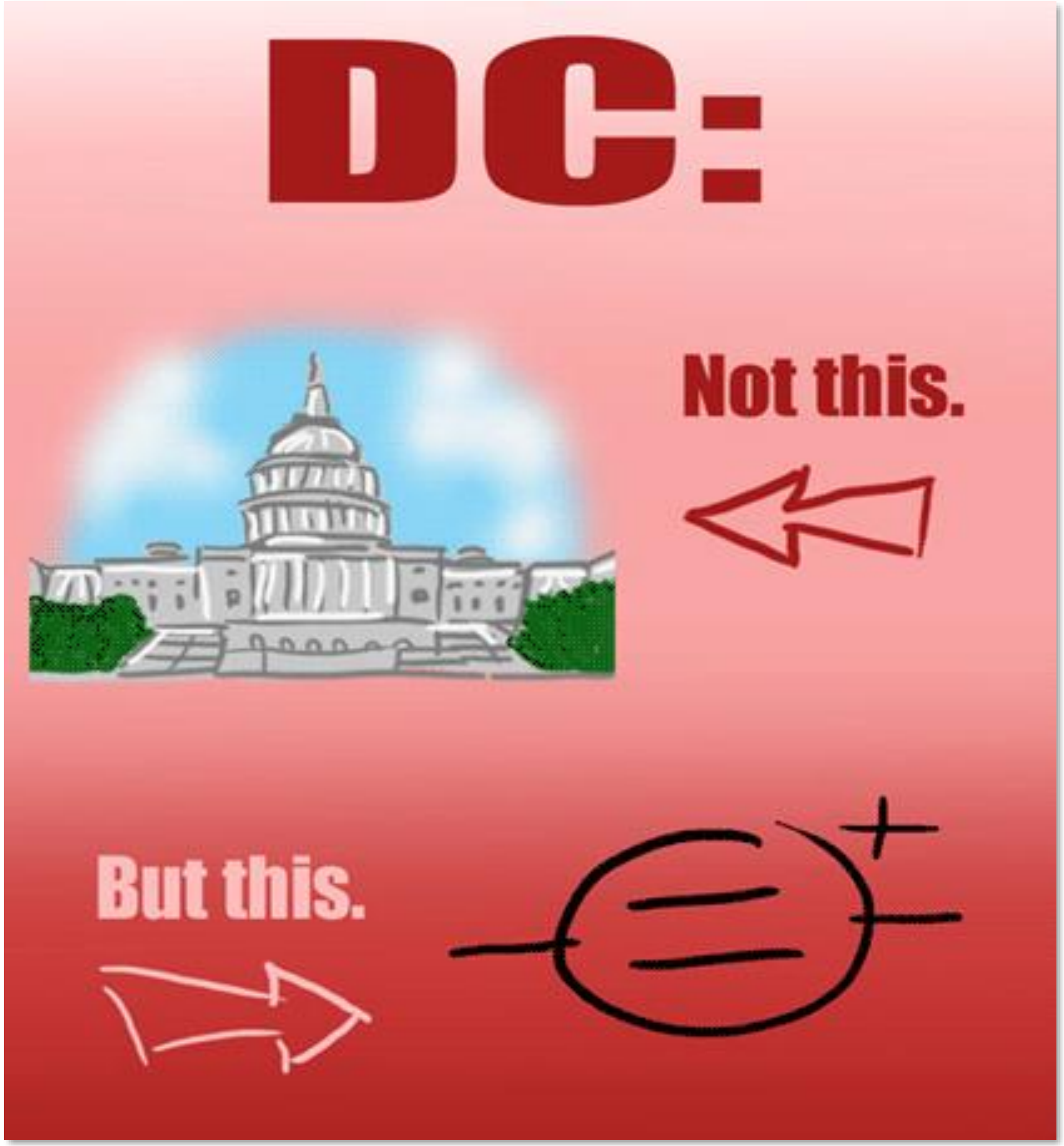
Power Electronics Group

i³ DC
Accelerates Energy Transition

- https://taltech.ee/en/power-electronics-research-group *(to be updated)*
- https://taltech.ee/en/i3dc-initiative



CALL FOR COLLABORATION!!!

We will welcome
collaboration on DC buildings
with interested partners
all over the World!

Feel free to contact us at
i3dc@taltech.ee

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QUESTIONS

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