D-Suite

Literature Review and Supplier Engagement

Future Networks

SP ENERGY NETWORKS

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Glossary of Terms

TERM	DEFINITION
AC	Alternating Current
AI	Artificial Intelligence
ARPA-E	Advanced Research Projects Agency-Energy
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
DC	Direct Current
DER	Distributed Energy Resource
DNOs	Distribution Network Operators
D-HF	Distributed Harmonic Filter
D-SOP	Distributed Soft Open Point
D-ST	Distributed Smart Transformer
EA	Energy Availability
ED2	Electricity Distribution 2
EMC	Electromagnetic Compatibility
ENA	Energy Network Association
EU	European Union
EV	Electric Vehicle
FACT	Flexible AC Transmission
FAT	Factory Acceptance Test
FEU	Forced Energy Unavailability
FOR	Forced Outage Rate
GaN	Gallium Nitride
GB	Great Britain
GHG	Greenhouse gas
GW	Gigawatts
HF	Harmonic Filter
HIL	Hardware-in-the-loop
HV	High Voltage
HVDC	High Voltage Direct Current
HVPD	High Voltage Partial Discharge Ltd
IGBT	Insulated Gate Bi-Polar Transistor
kV	Kilovolts
LCNI	Low Carbon Network Innovation
LCT	Low Carbon Technologies
LV	Low Voltage
ML	Machine Learning
MOSFET	Metal Oxide Semiconductor Field Effect Transistor

TERM	DEFINITION
MV	Medium Voltage
MVA	Mega-Volt Amps
MVAr	Reactive Mega-Volt Amps
MVDC	Medium Voltage DC
MW	Mega-Watts
NC	Normally Closed Circuit
NIA	Network Innovation Allowance
NIC	Network Innovation Competition
NO	Normally Open Circuit
NOP	Nodes of Potential
NPV	Net Present Value
OHL	Overhead Line
OPEX	Operational Expenditure
PD	Partial Discharge
PED	Power Electronic Devices
PHIL	Power Hardware-in-the-loop
PM	Project Manager
PQ	Power Quality
PV	Photovoltaic
R&D	Research and Development
RIIO-ED1	Electricity Distribution 1 Regulatory Period
SAT	Site Acceptance Test
SCS	Smart Control System
SDRCs	Successful Reward Delivery Criteria
SEU	Scheduled Energy Unavailability
SiC	Silicon Carbide
SIF	Strategic Innovation Fund
SOP	Soft Open Point
SPB	Soft Power Bridge
SST	Solid State Transformer
ST	Smart Transformers
STATCOM	Static Synchronous Compensator
THD	Total Harmonic Distortion
TRL	Technology Readiness Level
TVV	Thames Valley Vision
UK	United Kingdom
UKPN	UK Power Network
VSC	Voltage Source Convertor
WEEE	Waste Electrical and Electronic Equipment
Wh	Watt-hour

TERM	DEFINITION
WP	Work Package

Executive summary

The D-Suite Discovery Phase Strategic Innovation Fund (SIF) aims to explore the potential for power electronics solutions in LV distribution networks, considering a 'suite' of four technologies (STATCOM, Soft Open Point, Smart Transformer and Active Filters). The use of co-ordinated control, network integration into power electronic design, and supplier engagements were previously identified as a unique set of innovations the D-Suite project could leverage to achieve a high impact Beta stage demonstration project.

This report outlines a holistic literature review and supplier engagements undertaken as part of this D Suite project to explore the potential of these and other technology innovation approaches. A survey of 54 related projects in Europe and the US highlight the complexity of the design of power electronic devices for grid applications. Based on those projects, a set of nine challenges to widespread uptake were identified, with six broad technology innovation classes capturing the approaches taken to address those challenges. In general, projects exploring power electronics for grid-connected, low voltage AC system applications are not common, and so there is good potential to break new ground. A subsequent detailed literature review into those six technology classes shows a range of techniques to improve competitiveness and applicability of power electronics in LV grids.

It is recommended that future demonstration projects should push forward with multiple complementary technology innovation classes, as no one innovation can address all challenges. Supplier engagements show a range of companies that have potential to deliver one or more of the D-Suite solutions, but note that future stages should continue to explore increased engagement to maximise benefits.

1. Introduction

As energy systems transition towards a new net zero paradigm, network operators must maintain adequate capacity to supply increasing demand whilst maintaining power quality and appropriate levels of service. Conventional capacity constraints limit the power that can be transferred due to voltage limitations, the maximum currents that can pass through lines and substations, or the equipment that can be safely connected to the network whilst ensuring appropriate fault level for a network's protection scheme. Power quality and service quality cover issues such as flicker, harmonics and distribution system reliability, resulting in inconvenience (and potentially lost earnings) for customers, or even damage to network or customer assets. DNO's operating licences are granted by the regulator and are expected and incentivised to provide an excellent service for customers in these regards.

It is well known that all these system requirements will be put under tremendous pressure in LV networks due to heat and transport electrification, and the uptake of other low carbon technologies such as solar photovoltaics and battery systems [1]. High costs and potential disruption associated with conventional reinforcement activities are therefore driving DNOs to explore a wide range of new approaches to enable them to address the system needs via alternative means, for example through non-wires alternatives and flexibility markets.

Conversely, there is an increasing technology pull from advanced power electronics solutions that have been developed for both electrified transport and grid-connected renewables. For example, Silicon Carbide power converters have been included within the drivetrain of mass-produced electric vehicles [2], resulting in higher efficiency than conventional Silicon-based power electronics, In parallel, the widespread rollout of converter interfaced generation (particularly wind and solar photovoltaics) are producing increasing confidence in the reliability and performance of power electronic solutions.

The D Suite project leverages both 'market pull' and 'technology push', exploring the potential of a class of LV power electronic devices (PEDs), the 'D Suite', for providing valuable system services to support the energy system's transition. It has been proposed that three technological innovation approaches are followed of co-ordinated control, increased engagement with supply chains, and network integration within the power converter design, aiming to enable and demonstrate the potential of D Suite technologies as DNO-owned PED assets that can effectively provide network services.

This report describes efforts, within the D Suite project, to explore the opportunities and challenges facing PEDs, based on a review of previous projects, academic literature, and through some initial discussions with potential suppliers of D Suite technologies. This holistic approach aims to provide context for the proposed innovative solution that D Suite is offering, whilst also evaluating the potential of alternative technologies that could be utilized to improve the D Suite offering. A list of potential suppliers of D Suite technologies are also provided that a future phase of this project (or other projects exploring LV power electronics).

1.1 THE D-SUITE SOLUTION

The D Suite project has proposed a suite of four technologies to address these issues, namely Static Compensator (STATCOM), Smart Transformer (ST), Soft Open Points (SOPs), and Harmonic Filters (HFs), with the prefix 'D-' indicating they belong to the D-Suite (e.g., D-STATCOM or D-ST). Between them, these technologies can address capacity, service quality and power quality issues. In this section, these four technologies are introduced to highlight the main mechanisms by which they can provide network services required within LV networks.

1.1.1 D-STATCOM

A D-STATCOM is a PED that is constructed by connecting power electronics in shunt across a DC link capacitor or other DC storage technology (typically with a capacity suitable only to maintain the DC voltage, or to inject power during transients). Using appropriate control across the power electronics, currents drawn by the device I_A, I_B, I_C can be adjusted to inject or draw reactive power, or provide power balancing if there is significant current unbalance, as shown in Figure 1.1.

Subsequently, the D-STATCOM can provide a service to address a range of system needs – it has potential to:

- adjust reactive power output to address voltage congestion,
- adjust reactive power output for voltage optimization (as part of a conservation voltage reduction scheme),
- adjust reactive power output to improve power factor to release headroom and reduce losses,
- respond to voltage transients (sags, swells or rapid voltage change) by injecting real and reactive power,
- inject harmonic currents to mitigate network harmonics,
- reduce current and voltage unbalance caused by nonlinear or asymmetrical loads [3].

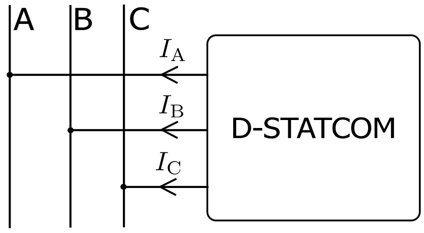

Figure 1.1. LV Distributed STATCOM (D-STATCOM)

1.1.2 D-ST

MV to LV smart transformers can have a range of topologies and designs, but the core principle is to provide improved performance or functionality as compared to a conventional transformer. Figure 1.2 shows this functionality, with the D-ST transforming power from high to low voltage. As compared to a conventional HV/LV, fixed-tap transformer, the ST can modify the voltage on the main LV busbar (i.e., it can choose V_A, V_B, V_C), and potentially inject reactive power to the MV network Q_{MV} that can increase the hosting capacity of distributed energy resources [4].

The D-ST therefore has potential to:

- adjust HV reactive power to manage HV voltage constraints, support voltage optimization, or correct power factor to release headroom and reduce losses,
- mitigate against harmonics on both HV and LV systems,
- adjust LV voltages to maximise LV hosting capacity,
- adjust LV frequency of supply in the LV system.

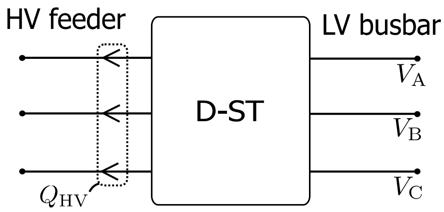

Figure 1.2. Distributed Smart Transformer (D-ST)

1.1.3 D-SOP

In many contexts, electrical distribution networks are built meshed but operated radially, to enable unidirectional power flow and simpler protection. In these systems, 'normally open points' exist which are switches within the distribution network that enable reconfiguration in the case of an outage or maintenance within the system. D-SOPs are PEDs that can replace these normally open points, enabling real and reactive power to be transferred between adjacent feeders, as in Figure 1.. It can also balance the load, regulate the voltage, increase reliability, and enhance the flexibility and resiliency of the network [5].

This D-SOP therefore has potential to:

- transfer real power and inject reactive power to address voltage and thermal congestion,
- transfer real power and inject reactive power to reduce peak flows and improve power factor, reducing losses,
- provide voltage support to enable voltage optimization,
- inject harmonic currents to mitigate against network harmonics.
- Note that the D-SOP can have a topology that is similar to two D-STATCOMs connected in series, and so is likely to have similar functionality (although D-SOPs are constrained to be placed where there is a suitable normally open point).

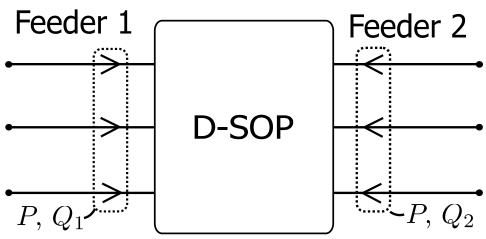

Figure 1.3. Distributed Soft Open Point (D-SOP)

1.1.4 D-HF

The D-HF a device that can reduce the harmonic distortion in the current or voltage waveform of a distribution network. It can be designed to inject harmonic currents, as in Figure 1., with passive components, active components, or a combination of both. Its main purposes is to reduce harmonics resonance [6] and can also improve power factor. The topology and construction of a D-STATCOM and D-HF may be similar, with the main difference that the D-HF design is optimized to provide higher frequency harmonic filtering, where a D-STATCOM might be more likely to be expected to provide significant reactive power compensation.

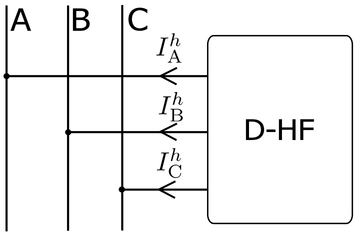

Figure 1.4. Distributed Harmonic Filter (D-HF)

2. Literature Review of Challenges and Opportunities

D Suite proposes to explore the use of PEDs in LV networks to provide much-needed system services. In Section 2.1 we perform a literature review of previous projects to understand challenges and opportunities (research gaps), identifying technologies innovations that have potential to enable PEDs to effectively provide system services in the medium term. Subsequently, in Section 2.2 we then explore the potential for these identified technologies to address those challenges, highlighting the mechanism by which these innovations could support these new technologies.

2.1 SUMMARY OF PREVIOUS PROJECTS AND CHALLENGES

There are many innovation projects, both within the UK and internationally, that have looked to develop innovative power converter technologies for a range of applications. As compared to previous projects, D-Suite is unique as it has a focus on

- LV distribution (rather than MV or HV distribution),
- grid-connected systems (rather than on islanded microgrids),
- and conventional AC systems (rather than mixed AC/DC or DC distribution systems).

In some sense, each of these three aspects are unusual to see in previous projects as they are, in themselves, very high TRL (i.e., the AC, LV, grid-connected system is almost universal). Research projects therefore often focus on more complicated arrangements such as microgrids. Additionally, D Suite looks to develop a suite of network solutions, based on a common set of design principles, where previous projects might typically focus on one class of converter.

In Section 2.1.1, we first describe our review of international projects that have been identified by searching the Horizon program's database (for Europe-based projects) and the ARPA-E projects database (for US-based) projects. In Section 2.1.2, these projects are analysed and categorized into a set of nine challenges facing power electronics solutions, and six technology classes, to illustrate where focus has been and consider the potential of the D Suite approach. Finally, in Section 2.1.3, we briefly describe the main findings from five UK-based innovation projects, as identified from the ENA Smarter Networks Portal, whose findings are then considered subsequently in Section 3.3.

2.1.1 International projects

The project search internationally has been based on (i) Horizon Europe's CORDIS database, and (ii) the US government's ARPA-E project database. For each of these databases, searches have been conducted for 'power electronics', 'power converter', and 'soft open point'. For the CORDIS database, categories of 'power engineering', 'electric power distribution', 'energy conversion' were commonly reported in the projects considered. For the ARPA-E database projects were in categories of 'protection', 'grid', 'electricity generation and delivery', 'storage', 'electrical efficiency'. Nevertheless, both database searches were undertaken without a filter on those topics specifically (to ensure a wide view of projects).

The list of relevant projects, as well as their core technologies, start and end dates, and the challenges they address are given as an appendix. As the D Suite project is unique in its approach (in terms of use of PEDs within AC grid-connected LV grid systems, as described in Section 2.1), there are few projects which are as well-placed as previous UK-based demonstration projects which could have potential to support LV power electronics. In total, 54 projects were reviewed. From the project themes, a set of nine main challenges were identified (Table 2.1) and six technology innovation classes that describe the methods used to address these challenges (Table 2.2).

Table 2.1. List of challenges identified in projects surveyed.

Challenge	Abrv.
Cost	Co
Maintenance & reliability	M&R
Maintaining power quality	PQ
Thermal management	ThM
Cyber security	CS
Stability and controllability	S&C
Sustainability	Su
Protection	Po
Personnel	Pe

Table 2.2. List of technology classes identified in projects surveyed and abbreviations.

Technology class	Abrv.
Advanced design	AD
Coordinated control	CC
Wide bandgap devices	WBG
Advanced manufacturing	AM
Engaging supply chains	ESC
Network integration	NI

2.1.1.1 Project breakdown: technology innovation classes

Technologies found in international projects were categorised into six key future technology classes: advanced design, co-ordinated control, wide bandgap devices, advanced manufacturing, engaging supply chains, and network integration. These technologies can be summarised as follows.

- Advanced design (AD). This technology class focuses on developing new and innovative designs for the power electronic converters themselves. Advanced design techniques may involve new topologies, AI or machine-learning based design techniques, and other advanced computational methods for effective converter design.
- Co-ordinated control (CC): Conventional power converter controls are fully decentralised. Coordinated control adds the potential for information sharing via communication between converters, and incorporation of measurements from sensors embedded within the distribution network. This can improve the utilization of the converters, reducing cost, and increase the stability and controllability during transients.
- Wide bandgap devices (WBG): Wide bandgap devices are an evolving class of semiconductor materials that offer significant advantages over traditional silicon-based devices. They have higher breakdown voltages, faster switching speeds, and lower losses, which makes them ideal for high-power and high-frequency applications. Wide bandgap devices can enable more efficient and compact power converters.
- Advanced manufacturing (AM). Advanced manufacturing techniques involve using new materials, processes, and tools to improve the production of power electronic devices. This can include the use of additive manufacturing, advanced packaging techniques, 3D printing, nano-scale fabrication, cooling methods or automated assembly processes. Advanced manufacturing can help

to reduce costs, increase production yields, and improve the performance and reliability of power electronic devices.

- Engaging supply chains (ESC). By engaging with power electronic supply chains and developing partnerships between different stakeholders, the whole energy system can benefit from shared knowledge, resources and expertise. Stakeholders include manufacturers, suppliers, researchers, and engineers within the network operator.
- Network integration (NI). Network integration refers to the process of developing the workflows required to design, plan and operate new network technologies (e.g., power electronic systems) with the power grid. This involves developing new standards, protocols, and planning and operational systems to enable power electronic systems to operate safely and reliably within the grid.

The projects explored cover these technologies, with a slight weighting towards advanced design and manufacturing technologies, with fewer exploring co-ordinated control or novel wide bandgap technologies Figure 2.1.

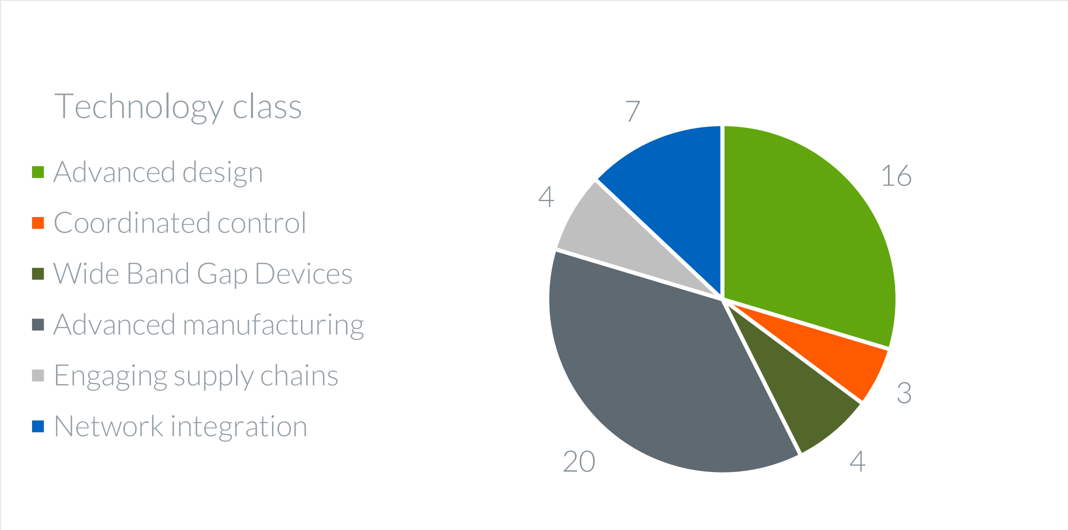

Figure 2.1. The primary technology class of the 54 EU-based Horizon projects and US-based ARPA-E projects

2.1.2 Challenges to uptake of power electronics-based solutions in LV grids

The challenges that the these presented projects address are summarised into nine categories: cost; maintenance and reliability; sustainability; power quality; thermal management; cyber security; stability and controllability; protection; and personnel. These challenges are summarised as follows.

Cost (Co). Power converters require expensive materials, complex fabrication processes, and specialised components as compared to technologies used in conventional reinforcement. Additionally, costs associated with design and testing of power electronics devices can be significant. As a regulated utility, DNOs must provide value for money for customers. Reduction in the cost of power converter technologies is a primary concern for all power electronic solutions to grid problems [7].

Maintenance and reliability (M&R). Network operators are responsible for ensuring safety within their licence area, protecting life and property, and network reliability is a key performance indicator. Power electronics must demonstrate that they operate at a level that is acceptable for network companies. In this regard, they are competing against highly mature technologies, and so achieving acceptable reliability is challenging [8, 9].

- Sustainability (Su). The manufacture of power electronics is highly energy and materials intensive whilst the complexity and diversity of the materials used in power electronics makes recycling and safe disposal challenging. To address these issues, as well as to encourage a more resource-efficient and circular use of resources, creative techniques and solutions are needed [10].
- Power quality (PQ). Power electronic solutions can impact on power quality by interacting with non-linear loads or other power electronic-based systems to affect voltage waveforms, increasing distortion, causing parasitic harmonic injections, or even affecting transients. These can affect the performance of other network equipment and loads, and so the network operator must ensure that power electronic-based solutions do not adversely affect power quality [11].
- Thermal management (ThM). Heat produced as losses by power electronic devices and systems must be carefully dissipated or it will damage components.
- Cyber security (CS). Power electronics-based systems must protect and be resilient to cyber threats and attacks. By contrast, conventional reinforcement in distribution networks is built of passive components, and so present fewer opportunities for attackers to disrupt grid operations. Innovative solutions and strategies are needed to monitor, detect, prevent and mitigate cyber security problems and to ensure the security and resilience of power electronic systems [12].
- Stability and controllability (S&C). Power converters can respond quickly to changing grid conditions to provide voltage support or dynamically reroute power flows to avoid equipment overloads. However, these controls requires new methods to analyse and ensure converters act together to avoid any potential for oscillations or instability of power flows and voltages within the distribution system [13].
- Protection (Po). Power electronic devices are susceptible to equipment damage or even safety hazards from overcurrent and overvoltage during short-circuit conditions when there is a fault. Power electronics designers therefore must incorporate integrated protection mechanisms as part of the converter systems, including overcurrent protection, overvoltage protection, and thermal protection, and this can often be a substantial part of the overall cost and volume of the design.
- Personnel (Pe). Power electronics is a complex and multidisciplinary field that requires a combination of skills and knowledge in disparate areas of electrical engineering, electronics, and control. As a result, it is a major challenge to find individuals with the required knowledge and expertise in both power electronics and power distribution. This shortage is partly due to the relative novelty of the field (as compared to, for example, variable speed drive applications of power electronics), as well as the lack of specialized training programs.

Given the importance of cost and reliability of converters, it is unsurprising that many projects explored technologies designed to address these challenges. On the other hand, fewer projects explored thermal management or cyber security issues directly (Figure 2.2).

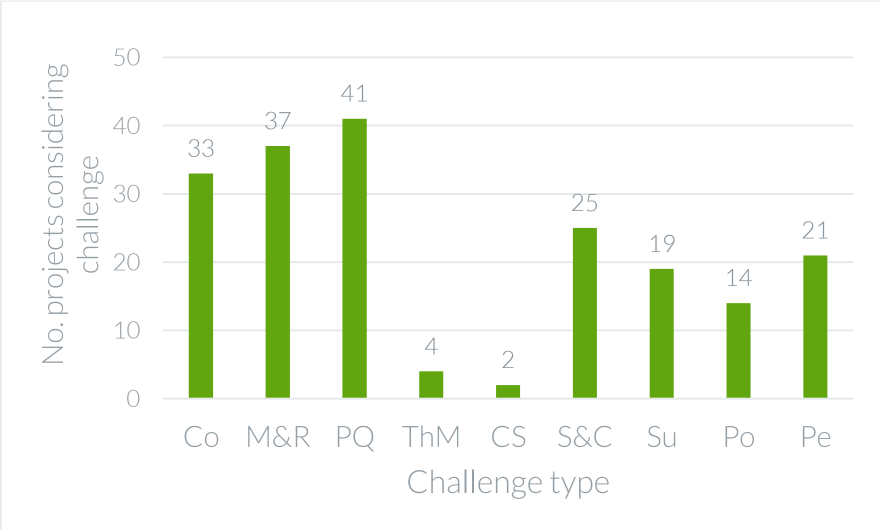

Figure 2.2. Breakdown of challenges addressed through the 54 EU and US-based projects considered.

2.1.3 UK-Based Projects

UK DNO's have led to a number of large demonstration innovation projects whose findings are public (through the Smarter Networks Portal). These projects are well-known to DNO's within the UK, and so only a smaller number of projects have been identified to review findings for this report. The projects considered are the FUN-LV project, Active Response, Thames Valley Vision, LV Engine, and Harmonic Mitigation. In this section, we briefly summarise the aims of these projects, with the main learning outcomes discussed directly in Section 3.3.

Flexible Urban Networks-Low Voltage (FUN LV) project explored three interventions for increasing the capacity of urban networks and concluded in 2016. A substantial aspect of the project was spent implementing Soft Open Point technology in LV networks, it concluded that the TRL level was too low at this stage for full roll-out. However, it was suggested that further projects could lead this to be an effective solution [14].

Active Response followed on from the FUN LV project, and deployed SOP technology across a further set of sites across the service area of UKPN. Newer technology was used (for example, SiC wide bandgap semiconductors) to address some of the issues of FUN LV [15].

New Thames Valley Vision explored the use of low voltage energy storage to address network congestion. The TRL remained too low for full roll-out however the potential of the technology was demonstrated [16].

LV Engine explored the use of MV to LV Smart Transformers for a range of system services and topologies, including with innovative approaches such as usage of the DC link for distribution of power (e.g., for electric vehicle fast charging [17]).

Harmonics Mitigation explored the use of changing inverter settings to mitigate harmonics in HV distribution networks [18].

2.2 OPPORTUNITIES TO ADDRESS CHALLENGES FACING POWER ELECTRONICS-BASED SOLUTIONS

In the previous section, nine challenges were presented, and six technology classes presented as technical solutions as means a of addressing those challenges. In general, some of these technologies will address some challenges, but not others.

In general, the documentation from projects obtained from the EU Horizon CORDIS database and US-based ARPA-e database had less detail than project counterparts in the Smarter Networks Portal.

Therefore, in this section, details as to how each technology class can address change, based on more detailed descriptions drawn from academic or other grey literature.

Table 2.3 presents the finding of this review, presented as a matrix mapping the challenges to PED uptake by DNOs against the technology innovations that have been explored in recent projects. A score of 1-3 is given to identify the estimated effectiveness of each technology to address the necessary challenges, with a '1' indicating limited or no impact, and a '3' presenting the solution as a highly effective solution (challenges are outlined in Section 2.1.2 and technologies in Section 2.1.1.1). From Table 2.3, it can be seen that there are few technologies which are highly effective, and the technologies can only affect three or four of the nine challenges to PEDs. Nevertheless, many of the innovations have potential to improve the cost, reliability, thermal management and sustainability of converters can be addressed by three or more innovations surveyed. In the rest of this section, we cover how these technologies and challenges are linked.

Table 2.3. Challenge-technology matrix for power electronics-based solutions.

Technology or innovation class	Challenge to PED uptake at LV by DNOs								
	Co	M&R	PQ	ThM	CS	S&C	Su	Po	Pe
AD	2	1	1	2	1	1	2	1	1
CC	1	1	1	2	2	3	2	1	1
WBG	1	1	1	2	1	2	1	1	1
AM	2	2	1	3	1	1	1	2	1
ESC	2	2	1	1	1	1	2	1	3
NI	1	2	2	1	1	1	2	2	1

Key	
Neutral / ineffective	1
Effective	2
Highly effective	3

2.2.1 Wide bandgap devices: impacts on PED challenges

After many decades of development, Silicon (Si) devices are reaching the theoretical limits of their performance in many applications. WBG materials, such as Gallium Nitride (GaN) and Silicon Carbide (SiC) have been demonstrated to outperform Si semiconductors in power converter applications, with lower switching losses, higher switching frequency capabilities, and improved thermal management performance. WBG are rated for higher voltage applications as they have greater voltage blocking capability due to the to their higher electric breakdown field.

Cost: WBG devices are more expensive at the component level in comparison to Si technology today. Investing in a system with WBG devices could still today generate savings through improved power density and reduced system size, as well as lower switching losses. However, in the short-medium term, this will be dependent on realising those wider system benefits – for example, in [19], a price performance comparison considering losses is considered, showing GaN as five times the cost of Si IGBTs.

Thermal Management: The WBG semiconductors can operate at higher temperatures compared to the Si counterparts due to the wider band gap and higher electric breakdown field. SiC requires less cooling the Si as it has a lower junction to case thermal resistance [20]. The increase in power density afforded from the technology requires thermal management for device performance and reliability.

Stability and Control: SiC is currently used in the controller of several commercial applications such as Tesla Model 3 since 2017, low power LED/optical applications, photovoltaic converters [21]. The higher switching frequency of the WBG devices results in lower current ripple [20], although it is known that reflected wave phenomena by faster switching frequencies can cause power quality issues. Employing PWM methods of control instead of passive filters can limit the reflected voltage and has been used in motor drive applications [20].

Sustainability: The energy intensity of the semiconductor industry is widely known and is growing more with increasing demands. The environmental cost associated with sourcing, manufacturing, transportation, usage and end of life disposal of the technology; all requires visibility [22]. From cradle to grave, the full impact of the life cycle is challenging to capture. It was estimated that the manufacturing of the chips is the most energy intensive process accounting for approximately 63% of the total emissions over the products lifetime [23].

A life cycle assessment conducted in [23] compares onboard car chargers made from WBG devices and Si. The study highlighted the improved system efficiency and reduced footprint has a significant impact on the overall carbon footprint in favour of WBG. Considering the higher cost of the SiC technology whilst considering the smaller footprint compared to the Si technology, the analysis shows that the SiC MOSFET design had lower CO_2 emissions for material and assembly when compared to Si-IGBT and Si-MOSFET designs. The energy lost through charging was reduced with the SiC design which offsets the additional system cost from manufacturing. Considering the improved system efficiency, the total wasted energy is reduced which argues in favour of the longer payback period for greater system efficiency.

Protection: As with all electronic circuits, fault protection is required to protect the semiconductors from fault conditions. WBG devices have higher breakdown voltages compared to that of silicon, however the current spikes during a fault condition can limit the technology. Currently, SiC is used in fault critical applications and meets the reliability standards [24]. Research continues to assess the reliability of GaN after short circuit events. It is recommended to check the GaN device after a fault condition to assess the long-term impact [25] as the chips have been found to survive limited short circuit events before failing [26].

2.2.2 Co-ordinated control: impacts on PED challenges

Coordinated control by PEDs can provide the opportunity to increase the utilization of those systems during the periods when they are required.

Cost: The initial cost of coordinated control is higher compared than decentralised control due to increased requirements for sensors and communications. However, there are potential for lower system operating costs, leading to cost savings overall [27].

Cyber Security: Coordinated control is more prone to a cyber-attack than a decentralized control scheme, due to additional an increased number of vulnerabilities; however, if the control is distributed, then there is no central controller (as in centralized control) that could lead to catastrophic failure. With suitable security protocols in place, control schemes can detect and mitigate against the risk of cyber-attacks [28].

Stability and control: Communication between PEDs allows for a co-ordinated response to disturbances, greatly improving stability and controllability. Fibre-optic communications means that delays in communication can be extremely small, definitely much faster than the line frequency of 50 Hz.

Many works considering the differences between decentralized and co-ordinated control are based on PEDs that are customer-owned (e.g., electric vehicles or solar inverters). For example, it is described in [29] how it is possible for EV chargers to tackle issues such as voltage stability, but that coordinated control schedules EVs more effectively. Similarly, unforeseen events can be mitigated against more effectively [30].

2.2.3 Advanced design: impacts on PED challenges

Advanced design covers a range of techniques that are used to optimize the expected performance of a PED, with that performance depending on many design points such as operating frequency, the filter capacitance and inductance. The optimisation techniques will build a converter within these constraints for the given characteristics such as power density, permissible Total Harmonic Distortion (THD), losses and weight. Designing for the most cost effective solution is typically at odds with maximum system reliability, and so multi-objective optimisation is required in converter design [31].

There are many advanced design methods that can be used to improve converter performance, here we focus on three techniques.

- Metaheuristic optimization,
- Artificial Intelligence (AI) and Machine Learning (ML),
- Design for Reliability.

It is interesting to note that there can be disagreements about the appropriateness of these techniques for a given problem. For example, metaheuristic algorithms are have been criticised for their dependence on trial and error and potential for poor computational efficiency [32].

Cost: As described previously, the cost of a power converter is closely linked to other performance metrics (e.g., weight, volume). Nevertheless, the use of metaheuristics, AI, ML or other advanced computational design methods can provide increased solution exploration and faster performance prediction, providing a higher performance pareto front. For example, a 'earthquake' algorithm-based metaheuristic optimisation was used for inductor selection within a DC-DC converter design, resulting in an inverter with reduced ripple, increased operating power range and improved the overall converter efficiency [33]. There are associated high computational costs associated with the design stage – in these cases, other AI approaches (such as ML) may be more effective than metaheuristics [34].

Maintenance & Reliability: The reliability of power converters is closely related to its long-term operation, and so design techniques often do not explicitly model this aspect, i.e., the models do not include the root causes behind failures [31]. Nevertheless, better circuit design, thermal management, and using quality material in the design can result in better and more reliable performance of the power converters [35]. Additionally, fast modelling of thermal cycles (as in, e.g., [36]) could potentially open up options to include reliability more directly in future.

Power Quality: The waveform generated by an inverter defines the filter required to limit THD. Changing the switching angle can eliminate higher order harmonics caused by switching but that depends on non-linear equations which determine the switching angle. Selective harmonic elimination technique solved with metaheuristic methods showed a reduction in the THD compared to a sequential solution [31]. However, the lack of standards and testing methodologies in metaheuristics introduce challenges in specific energy grid optimisation [37].

Thermal Management: Optimisation of thermal management is a multi-objective optimisation with considerations such as heat sink sizing as a function of a thermal resistance along with optimal duty cycle, component sizing and location. [38] were able to improve the system performance of a battery storage system by 7.8% by minimising the temperature and battery layout. [39] used a metaheuristic approach whilst designing for the energy balance with phase change materials and thermal energy storage systems integrated in solar systems. The long-term thermoelectric analysis of power converters has also been demonstrated using AI techniques [36].

Sustainability: Typically, converter efficiency is a parameter considered as one of the objectives within optimal converter design. In power grids without a carbon-free power supply, increasing the efficiency reduces the carbon intensity of the converter. For example, AI has been used to design a power converter with 98% efficiency in [40].

2.2.4 Advanced manufacturing: Impacts on PED Challenges

Advanced manufacturing techniques have potential to influence converter design at many levels. The impact of the following techniques has been considered:

- 3D printing.
- Modularity.
- New energy storage system materials (capacitors, supercapacitors, battery storage).
- Advanced thermal management (heat pipes, phase change materials).
- Automated PCB manufacture.

Cost: Automation of printed circuit boards dramatically decreased the production time and cost of manufacture although, some through-hole components still require an operator to attach them manually. Research and development in 3D printing methods and materials are successfully printing magnetic components for use in converters, however, these are presently at very low voltage levels.

Maintenance & Reliability: Modularity offers design freedom as well as the ability to switch out broken modules without the need to replace the whole converter. Connecting multiple modules creates system scalability and flexibility within the system. Given the clear advantages, modularity is now being offered from industry and is high TRL, so can be incorporated into new designs.

Maintaining Power Quality: New energy storage materials (batteries, capacitors and supercapacitors) give power electronics increased capabilities to provide real and reactive power support and address power quality issues that they may otherwise cause. For example, a large bank of supercapacitors can maintain power output during transients.

Development in capacitors covers material changes and modified assembly techniques including 3D printing. Lithium-ion capacitors are a combination of a battery and a capacitor at the anode and cathode with a lithium ion to transmit the charged particles. Attempting to avoid further burden on the lithium resources, [41] propose sodium-ion capacitors which combine the energy density from batteries and power density from capacitors. Attempts to further increase the energy density of electrochemical capacitors is being researched with modified graphene materials. Designing the nanostructure of the capacitive plates is problematic with challenges around manufacturing processes and chemicals required for production [41].

Thermal Management: The use of Phase Change Materials (PCM) can be used to dissipate energy during transient conditions (e.g., energy is used to melt a solid, which then slowly cools to resolidify) [42]. A range of materials have been explored, such as organic PCMs, although the choice of material is affected by the semiconductor type due to variations in operating temperatures [43]. PCMs require a heatsink to draw the energy stored following the transient condition [42].

Systems such as heat pipes can utilize new manufacturing techniques to improve their performance. Heat pipes remove heat from the system via indirect liquid cooling [44], and (in contrast to phase change materials) operate continuously. For example, [45] showed the application of Selective Laser Melting (SLM) to create a 3D-printed hybrid heat pipe thermosyphon for cooling power electronics. 3D-printing the internal structure enabled them to enhance the capillary rates and evaporation rates. Sintered powder wick heat pipes can be used to further increase the internal surface area (used to operate the heat pump's capillary pumping force). The use of these pipes was shown to reduce the operating temperature when compared against natural convection [46]. Whilst graphene enhanced heat pipes are suggested to increase the heat dissipation compared to the copper pipes by 3.5 times [47].

Stability and Control: Active filters are built from capacitors, transformers and high voltage semiconductors. Semiconductor materials are discussed in detail in Section 2.2.1. As described previously in this section, increased energy density of electrical components such as supercapacitors can increase the availability of real power during transients [48].

There is also interest in the development of 3D printed magnetic cores for use in active filters, with examples of both transformers and inductors [49-51]. However, in all examples the magnetic permeability of the printed cores results in less power dense solutions compared to laminated counterparts. The complexity of the soft magnetic material grain structure requires further advancements before printed components can rival the laminated counterparts.

Sustainability: Waste from electrical and electronic equipment (WEEE) is one of the fastest growing waste streams globally. 3D printing components can limit waste material, however the chemicals and processes required to manufacture can lead to an increase in environmental footprint. Photocatalytic materials are being made as a result from e-waste such as printed circuit boards and integrated circuits [52]. Preventing e-waste from reaching landfill it is being using as a substitute for 20% of the concrete aggregate in new concretes which showed a positive reduction in environmental impact [62]. [53] refurbish waste carbon materials from supercapacitors for use as industrial grade electrodes.

Protection: From switch level to system level, adding redundancy to the system can provide fault tolerance, whilst parallel converters can improve reliability in fault conditions. In these cases, control techniques are required to ensure equal load sharing [54]. By adding a redundant switch with a diode and fuse in DC-DC converters [55] could cover short circuit fault conditions. The diodes and fuse isolate the faulty switch and the redundant switch engages instantaneously.

2.2.5 Engaging supply chains: impacts on PED challenges

The impacts of improvements in supply chains are not often discussed in detail within academic literature, as many of the data required to make quantifiable statements about impacts of improved supply chains is likely to be commercially sensitive. Nevertheless, the following general themes are reported in projects looking to engage supply chains.

Cost: Standardisation can support improvements in the quality and supply of power electronic components, with consumers benefitting as competition is introduced. Bulk production can lead to lower production costs.

Maintenance and Reliability: Standardisation of PED components will make it more likely in future that spares are available to maintain PEDs if there are faults, due to increased interchangeability of the components in PED. Furthermore, standardised components are likely to have better data on their lifecycle reliability characteristics. This will support the development of effective maintenance procedures or predictive maintenance.

Sustainability: A well-established supply chain can support sustainability goals by enabling more efficient use of resources and minimizing waste.

Personnel: An established supply chain will reduce the barriers to the education of engineers by providing a better-defined interface between network companies and more established companies. Standards could also be used as the basis for providing accreditation or qualifications that engineers could earn to provide them with further career opportunities.

2.2.6 Network integration: impacts on PED challenges

The integration of PEDs within networks today requires careful planning to adhere to the grid code. Some of the important factors which are highly affected with the proper integration of power electronics within the network are as follows:

Maintenance and reliability: By monitoring the health and operation of PEDs throughout their lifetime, DNOs can predict the likelihood of PED failures. This can allows predictive maintenance to reduce the risk of downtime caused by PEDs [56].

Power quality: Furthermore, the harmonic filters along with well-designed control algorithms can mitigate the harmonics within the network caused by non-linear loads and intermittent nature of renewable based generation [57]. This helps in improving power quality within the network and reducing the disruptions caused by these harmonics.

Sustainability: By specifying high efficiency, low loss power converters, PEDs can provide a lower carbon supply by reducing operational emissions attributed to them. Where these PEDs effectively manage congestion in networks with low carbon technologies, they can enable lower carbon operation of the grid [58].

Protection: With the help of these preventative measurements against the fault spreading, the power electronic devices greatly increase the reliability of the network [59]. The consideration of the network and conditions under faults is critical for the design of fault-tolerant power electronics. Works that consider such under and overvoltage and overcurrent conditions in PEDs for grid applications include [60].Where a PED contains a series element, the protection of the network is also crucial [61].

3. Supplier Engagement and Previous Project Findings

3.1 LIST OF SUPPLIERS

The list of potential suppliers for D Suite PEDs is shown in Table 3.1. This list of suppliers was collected by considering suppliers in previous projects (from OFGEM-funded innovation projects, EU Horizon projects and ARPA-e projects described in Section 2.1), and through a wider search using conventional search engines.

Table 3.1. List of potential suppliers for D Suite PEDs.

Supplier Name	Website
Schneider Electric	https://www.se.com/uk/en
Siemens	https://www.siemens-energy.com/global/en.html
BEVI	https://www.bevi.com/about-bevi
Alfen, Solutions	https://alfen.com/en-gb
P.E System Ltd	https://www.pe-systems.co.uk/
Smart Power Solutions	https://www.smartpowersolutions.com/
Bowers Electricals, Ltd	https://www.bowerselec.co.uk/
Rolla, Ltd	https://www.rolla.co.uk/
Turbo Power Systems	https://www.turbopowersystems.com/
Wilson Power Solutions	https://www.wilsonpowersolutions.co.uk/
Powerstar	https://powerstar.com/
Power Smart Control SL	https://powersmartcontrol.com/
SP Control Technologies	https://spcontroltechnologies.com/
Prodrive	https://prodrive-technologies.com/
IONATE	https://www.ionate.energy/
EFACEC	https://www.efacec.pt/en/

Generally, the small and medium enterprises (SMEs) within the list might focus on only one of either D-ST products, or D-STATCOM / D-SOP / D-HF products (the latter three are more closely related to conventional motor drives). All companies listed were contacted to give them an opportunity to discuss and clarify their capabilities. A number of discussions were had with suppliers to discuss the potential for engagement in future D Suite SIF phases, to discuss the potential benefits of the D Suite project to industry and supply chains, and to discuss the potential environmental impacts of their products.

3.2 LIFE CYCLE ANALYSIS FOR ASSESSING ENVIRONMENTAL IMPACTS

The UK's 2050 net zero carbon target requires the amount of greenhouse gases produced to equal the same amount that is removed. Determining the total environmental impact of a product requires an inspection of the product's whole lifecycle, from mineral extraction through production and operation to disposal. Standards, such as ISO 14040 and PAS 2080, can be utilized by DNOs to bring confidence that the assets that they install (including PEDs) are not inadvertently doing more harm than good due to embedded emissions for a given solution.

As discussed in Section 2, literature shows significant challenges for power electronics, and there are a number of tools that have been presented in the literature to investigate these issues. [62] have created a scale-able lifecycle inventory for the power electronics in an inverter unit. With use of the tool [63] created a LCA of an inverter for automotive. The study found that the manufacturing and losses from use dominate the environmental impact score. The metal and mineral extraction and depletion primarily due to manufacturing contributing to the majority of the environmental impact. Realisation of the carbon costs associated in the supply chain requires visibility of manufacturing techniques with material traceability. For example, the use of gold for good electrical contracts requires highly toxic chemicals such as cyanide to recover gold from virgin mines which can have a rate of extraction as little as 0.4g/t [64]. Supplier visibility will drive less energy intensive and harmful methods of material sourcing [65]. Component traceability with the bill of materials can enable re-use or repurposing of components at the end of the [66] ultimately reducing overall carbon footprint.

Discussions with suppliers have confirmed that these challenges exist for their products which have very wide supply chains for potentially thousands of components in a product. This is in part due to a fast-changing technological landscape, as described by the technology classes considered in Section 2.2. To support long-term carbon accounting, in the Alpha phase requirements should be made to further inform suppliers of the trajectory towards this requirement for business-as-usual LCA if these are rolled out in large numbers.

3.3 LESSONS LEARNED FROM UK PROJECTS APPLICABLE TO D SUITE

As highlighted in Section 2.1.3, lessons learned from five projects were reviewed to consider potential findings that can inform gaps and best practise required for the next phases of D Suite.

3.3.1 FUN LV

The FUN-LV project explored three technologies, with the use of power electronics (SOPs) relevant to the development of D Suite PEDs. Learning points from this project underscore the significance of understanding networks and the distribution of load prior during feasibility studies.

- In terms of planning and site selection, accurate knowledge of LV networks is crucial for identifying suitable installation locations, while detailed loading data is essential for effective LV modelling. Careful consideration should be given to cable ratings and appropriate actions during fault conditions. Accepting connection requests from large customers through programmable electronic devices may lead to overload, and alternative options like non-firm supply connections or load redirection can be considered.
- Installation, commissioning, logistics, and practical considerations involve site surveys, automated commissioning processes, communication network coverage assessment, compliance with regulations, and engagement with local authorities.
- Design considerations emphasise incorporating trial equipment learning, increasing onboard memory, improving self-protection systems, considering EMC requirements, and ensuring stable frequency in control feedback loops. Analysis and tools should address power factor correction trials, simple dashboards for visualisation, sophisticated monitoring systems, and understanding tool suitability and limitations.
- Project management findings stress efficient contract agreements, thorough specification completion and review, mid-delivery interaction, optimisation of reporting activities, and stakeholder engagement throughout different project phases.

3.3.2 Active Response

The Active Response project addresses challenges related to the increasing uptake of Low Carbon Technologies (LCTs), local generation growth, vehicle emission reduction targets, infrastructure costs, network complexity, and optimisation. As with FUN-LV, this project explored two PED solutions, D-SOPs and a novel HV Soft Power Bridge (SPB).

- As with FUN-LV, the learnings highlight the challenges of site selection. The high number of eligible sites entering the second feasibility stage required onerous data processing, prompting the refinement of techniques and increased automation in the future. Practical considerations and an understanding of technical and operational restrictions will be gained during the detailed design phase and trials, helping to filter appropriate sites.
- Lessons learned from the process include the importance of HV feeder interconnection data availability and the need for additional LV network data, which will inform the optimal placement of Soft Open Points (SOPs) and remote-control switches.
- It was found that phase angle measurements required (for assessing the feasibility of series-connected power converters) were challenging, and techniques for modelling and verifying maximum phase angles must be developed. The project found collecting and reconciling data from various sources to be time-consuming and challenging.

3.3.3 Thames Valley Vision

The TVV project reports were found to generally be less detailed than reporting from other projects, and so learnings relevant to D-Suite are more general. The project aimed to use a combination of data, consumer behaviour changes and targeted network interventions to reduce the need for network reinforcement. Project findings are generally positive, showing potential of PEDs with integrated storage in LV network demonstrated.

3.3.4 LV Engine

Smart Transformers (ST) are being tested as part of the LV Engine innovation project, with STs consisting of a Smart Control System (SCS) and a Solid-State Transformer (SST). As compared to D Suite's D-ST, a wider range of potential capabilities of the ST were considered, such has having LV DC distribution alongside the main AC grid feeding end-consumers. Key lessons learned from work package reporting include the following.

- The importance of procurement and market research (i.e., improved supply chain engagement). It is suggested that today there is a need for very close collaboration between manufacturers and distribution network operators (DNOs).
- PEDs can have more complex risks associated with them, for example DC leakage and corrosion.
- Where PEDs are used to supply LVDC systems, that protection strategies and fault response are carefully considered.
- There is significant scope for new ways of increasing engagement – for example, the project explored the use of holographic technology for project awareness, and sharing findings through industry working groups and technical guidance documents.

3.3.5 Harmonic Mitigation

The project explores co-ordinated control of inverters. It is relevant to D Suite as it explores issues around harmonics caused by PEDs, and how fast communications can be used to achieve improved controllability of harmonics, yielding a 55% in harmonic effects.

The project is at a lower TRL than other demonstration projects, and so there are many technical findings, such as sampling time issues which were solved by using a simplified network model. The project highlights the potential from introducing communication functionality between PED inverters for coordinated control, with potential of adjusting control systems gains based on the capacity of each inverter. Nevertheless, the complexity of these systems was recognized, with Hardware-in-the-Loop (HIL) testing emphasised to minimize risks prior to application on real systems.

4. Summary

This report covers a literature review and outlines supplier engagements undertaken as part of the D Suite SIF Discovery stage project. The report has explored a range of sources to explore the potential technology and innovation approaches that could be leveraged in the next SIF stage (or other project exploring the potential of PEDs for grid applications).

A database of 54 projects based in the EU or US has been developed and presented to explore the range of technologies that have been proposed. These suggest there are six broad technological innovation classes which address nine challenges to widespread uptake of PEDs in distribution grids. A range of mechanisms by which these can address the nine challenges were covered from academic and other grey literature.

The findings of the literature review and supplier engagements can be summarised as follows.

- Power converter designs for grid applications are complex and face a range of challenges to widespread uptake.
- It makes sense to push forward with a range of technology classes to increase the TRL, as no one technology class can effectively address all challenges.
- There are few innovation projects that explore the specific grid-connected, low-voltage AC systems highlighting there are good opportunities for impact from the D Suite project.
- A range of potential suppliers for the D Suite PEDs have been identified, future work should look for increased engagement.

Appendix: Power Electronics Projects Database

The method for searching and identifying the following projects relevant to D-Suite was outlined in Section 2.1. The technology categories (and their abbreviations) are described in Section 2.1.1.1, and the challenges the projects address (and their abbreviations) are described in Section 2.1.2. A project is listed as having 'High' relevance for D-Suite if it considers PEDs in the context of two of the three aspects of an AC, grid-connected LV system (as outlined in Section 2, these make D-Suite unusual). Otherwise, the project is reported as having medium ('Med') D-Suite relevance.

NO	TITLE	START DATE	END DATE	CATEGORY	CHALLENGE(S)									D-SUITE RELEVANT	LINK
					Co	M&R	PQ	ThM	CS	S&C	Su	Po	Pe		
P1	The next-generation silicon-based power solutions in mobility, industry and grid for sustainable decarbonisation in the next decade.	01-Jun-19	30-Sep-22	AM	✓	✗	✓	✗	✗	✗	✗	✗	✓	Med	https://cordis.europa.eu/project/id/826417
P2	High performant Wide Band Gap Power Electronics for Reliable, energy eFficient drivetrains and Optimization thRough Multi-physics simulation.	01-May-18	31-Oct-21	WBG	✗	✓	✗	✗	✗	✗	✓	✗	✓	Med	https://cordis.europa.eu/project/id/783174
P3	GaN for Advanced Power Applications.	01-Jun-21	31-May-24	WBG	✗	✓	✓	✓	✗	✓	✗	✗	✗	Med	https://cordis.europa.eu/project/id/101007310
P4	Massive InteGRATion of power Electronic devices.	01-Jan-16	31-Dec-19	CC	✗	✓	✓	✗	✗	✓	✓	✓	✓	Med	https://cordis.europa.eu/project/id/691800

NO	TITLE	START DATE	END DATE	CATE GORY	CHALLENGE(S)									D-SUITE RELEVA NT	LINK
					Co	M&R	PQ	ThM	CS	S&C	Su	Po	Pe		
P5	Digitalization of Power Electronic Applications within Key Technology Value Chains	01-Jan-23	31-Dec-25	ESC	✓	✓	✓	×	✓	✓	✓	×	✓	High	https://cordis.europa.eu/project/id/101096387
P6	Business scale up of an AI tool for the optimal design of power converters	01-Jun-20	31-May-22	AD	✓	×	×	×	×	×	×	×	×	Med	https://cordis.europa.eu/project/id/953971
P7	Harmonic identification, mitigation and control in power electronics-based power systems	01-Mar-13	28-Feb-18	AD	×	×	✓	×	×	✓	✓	×	✓	Med	https://cordis.europa.eu/project/id/321149
P8	All-scale predictive design of heat management material structures with applications in power electronics	01-Jun-15	31-May-18	AM	×	×	×	✓	×	×	×	×	✓	Med	https://cordis.europa.eu/project/id/645776
P9	3C-SiC Hetero-epitaxiALLy grown on silicon compliancE substrates and 3C-SiC substrates for sustaiNable wide-band-Gap powEr devices	01-Jan-17	30-Jun-21	WBG	✓	×	✓	✓	×	×	✓	×	✓	Med	https://cordis.europa.eu/project/id/720827
P10	New technological advances for the third generation of Solar cells	01-Jan-16	31-Dec-18	AM	✓	✓	✓	×	×	×	✓	×	✓	Med	https://cordis.europa.eu/project/id/687008
P11	The birth of a EUropean Distributed EnErgy Partnership that will help the largescale implementation of distributed energy resources in Europe (EU-DEEP)	01-Jan-04	30-Jun-09	ESC	✓	×	✓	×	×	✓	✓	×	✓	Med	https://cordis.europa.eu/article/id/87942-distributed-energy-resources-in-todays-power-system

NO	TITLE	START DATE	END DATE	CATEGORY	CHALLENGE(S)									D-SUITE RELEVANT	LINK
					Co	M&R	PQ	ThM	CS	S&C	Su	Po	Pe		
P12	Enhanced substrates and GaN pilot lines enabling compact power applications	01-May-15	30-Jun-18	ESC	✓	✗	✗	✗	✗	✗	✗	✗	✓	Med	https://cordis.europa.eu/project/id/662133
P13	Implementation of activities described in the Roadmap to Fusion during Horizon 2020 through a Joint programme of the members of the EUROfusion consortium	01-Jan-14	31-Dec-22	ESC	✗	✗	✗	✗	✗	✗	✗	✗	✓	Med	https://cordis.europa.eu/project/id/633053
P14	Silicon Carbide Power Technology for Energy Eficient Devices	01-Jan-14	31-Dec-17	AM	✓	✓	✓	✗	✗	✗	✗	✗	✓	Med	https://cordis.europa.eu/project/id/604057
P15	Sample power electronic module construction for testing, characterisation and manufacturability assessment	Mar-11	Aug-13	AM	✓	✓	✗	✓	✗	✗	✗	✗	✗	Med	https://trimis.ec.europa.eu/project/sample-power-electronic-module-construction-testing-characterisation-and-manufacturability
P16	Distributed multiport converters for integration of renewables, storage systems and loads while enhancing performance and resiliency of modern distributed networks	01-Sep-22	31-Aug-25	NI	✓	✓	✓	✗	✗	✓	✓	✓	✗	High	https://cordis.europa.eu/project/id/101069770
P17	Power Converters with Best In-Class Power Density	23-Apr-21	22-Apr-23	AD	✗	✗	✓	✗	✗	✗	✗	✗	✗	Med	https://cordis.europa.eu/project/id/101031029

NO	TITLE	START DATE	END DATE	CATEGORY	CHALLENGE(S)									D-SUITE RELEVANT	LINK
					Co	M&R	PQ	ThM	CS	S&C	Su	Po	Pe		
P18	Medium Voltage Direct Current Electronic Transformer	01-Jun-19	31-May-24	AM	×	✓	✓	×	×	×	×	✓	×	High	https://cordis.europa.eu/project/id/818706
P19	Diamond Converter and Arc fault DEtection for high-altitude operations	01-Jan-21	31-Oct-23	AD	×	✓	×	×	×	×	✓	✓	×	Med	https://cordis.europa.eu/project/id/101007868
P20	Future Oriented Renewable and Reliable Energy SIC Solutions	01-Oct-22	30-Sep-26	AM	✓	✓	✓	×	×	×	×	×	×	High	https://cordis.europa.eu/project/id/101075672
P21	Advanced Smart-grid Power dIstRibution systEm	01-Sep-16	29-Feb-20	AD	×	✓	×	×	×	✓	✓	×	✓	High	https://cordis.europa.eu/project/id/717091
P22	Hydropower Extending Power System Flexibility	01-Sep-19	31-Aug-23	NI	×	✓	✓	×	×	×	✓	×	✓	Med	https://cordis.europa.eu/project/id/857832
P23	Renewable Energy EMPOWERing European and InDian communities	01-Jul-21	31-Dec-24	NI	×	✓	✓	×	×	✓	✓	×	✓	High	https://cordis.europa.eu/project/id/101018420
P24	Innovative controls for renewable sources Integration into smart energy systems	01-Dec-15	30-Nov-19	CC	✓	✓	✓	×	×	×	×	×	✓	Med	https://cordis.europa.eu/project/id/675318
P25	INnovative SmarT Electric Power Distribution	01-Feb-17	31-Jan-23	AD	×	✓	✓	×	×	✓	✓	✓	×	Med	https://cordis.europa.eu/project/id/738064
P26	FREquency Security of Low-INertia electrical Grids	01-Jul-21	30-Jun-23	AD	×	×	×	×	×	✓	✓	✓	×	Med	https://cordis.europa.eu/project/id/101031512
P27	Smart Synchronous inverter for grid's stability	01-Sep-16	31-Aug-18	NI	✓	✓	✓	×	×	✓	×	×	×	High	https://cordis.europa.eu/project/id/717516

NO	TITLE	START DATE	END DATE	CATE GORY	CHALLENGE(S)									D-SUITE RELEVANT	LINK
					Co	M&R	PQ	ThM	CS	S&C	Su	Po	Pe		
P28	Electric distribution grid identification based on complex network theory using GIS information and limited grid monitoring and smart metering	01-May-22	30-Apr-24	AD	×	×	✓	×	×	✓	×	×	×	High	https://cordis.europa.eu/project/id/101029711
P29	Advanced Power Converters for Universal and Flexible Power Management in Future Electricity Networks	01-Mar-06	31-Aug-09	AM	✓	✓	✓	×	×	✓	×	✓	×	Med	https://cordis.europa.eu/project/id/19794
P30	Greenverter a revolutionary power converter technology to reduce environmental and economic losses due to electro pollution	01-Aug-19	31-Jan-20	AM	✓	✓	✓	×	×	✓	✓	×	×	Med	https://cordis.europa.eu/project/id/875715
P31	Electric LOsses Balancing through integrated STorage and power Electronics towards increased synergy between Railways and electricity distribution networks	01-Jun-18	31-Aug-22	NI	✓	✓	✓	×	×	✓	×	×	×	High	https://cordis.europa.eu/project/id/774392
P32	Advanced Solid State Transformers	01-Jan-18	30-Jun-22	AM	×	✓	✓	×	×	×	✓	×	✓	High	https://cordis.europa.eu/project/id/765774
P33	Towards Intelligent DC-based hybrid Grids Optimizing the network performance	01-Sep-20	31-Aug-24	AD	✓	×	✓	×	✓	✓	×	✓	×	High	https://cordis.europa.eu/project/id/957769

NO	TITLE	START DATE	END DATE	CATEGORY	CHALLENGE(S)									D-SUITE RELEVANT	LINK
					Co	M&R	PQ	ThM	CS	S&C	Su	Po	Pe		
P34	Innovative HV Solid-State TrAnsformer for maximizing Renewable energy penetration in energy distribution and transmission systems	01-May-22	31-Oct-25	AM	✓	✓	✓	×	×	×	✓	×	×	Med	https://cordis.europa.eu/project/id/101069702
P35	FUTURE UNIFIED DC RAILWAY ELECTRIFICATION SYSTEM	01-Dec-19	30-Nov-21	NI	✓	✓	✓	×	×	×	✓	×	×	Med	https://cordis.europa.eu/project/id/881772
P36	The Highly Efficient And Reliable smart Transformer (HEART), a new Heart for the Electric Distribution System	01-May-14	30-Apr-19	AM	✓	✓	✓	×	×	×	×	×	×	High	https://cordis.europa.eu/project/id/616344
P37	Artificial Intelligence for Next Generation Energy	01-Jan-21	31-Dec-23	AD	✓	✓	✓	×	×	×	✓	✓	✓	Med	https://cordis.europa.eu/project/id/101016508
P38	Low-Insertion HVDC Circuit Breaker	01-Sep-12	31-Jul-13	AM	✓	×	✓	×	×	✓	×	✓	×	Med	https://arpa-e.energy.gov/technologies/projects/low-insertion-hvdc-circuit-breaker
P39	Fuel-Free Compressed-Air Energy Storage	13-Sep-10	04-Jan-11	NI	✓	✓	✓	×	×	×	×	×	×	Med	https://arpa-e.energy.gov/technologies/projects/fuel-free-compressed-air-energy-storage

NO	TITLE	START DATE	END DATE	CATEGORY	CHALLENGE(S)									D-SUITE RELEVANT	LINK
					Co	M&R	PQ	ThM	CS	S&C	Su	Po	Pe		
P40	Utility-Scale Silicon Carbide Semiconductor	09-Jan-10	28-Feb-13	AM	✓	×	✓	×	×	×	×	×	×	Med	https://arpa-e.energy.gov/technologies/projects/utility-scale-silicon-carbide-semiconductor
P41	Modular Solid State Transformers	02-Dec-18	11-Nov-21	AD	✓	✓	×	×	×	✓	×	×	×	High	https://arpa-e.energy.gov/technologies/projects/modular-solid-state-transformers
P42	Semiconductors that Improve Electricity Flow	02-May-13	31-May-16	AM	×	✓	✓	×	×	✓	×	×	×	Med	https://arpa-e.energy.gov/technologies/projects/semiconductors-improve-electricity-flow
P43	Solid State Circuit Breakers for Microgrids	18-Dec-17	31-Dec-22	AM	✓	✓	✓	×	×	×	×	✓	×	Med	https://arpa-e.energy.gov/technologies/projects/solid-state-circuit-breakers-microgrids
P44	High-Performance Transistors	02-Nov-13	08-Oct-14	AM	✓	×	×	×	×	×	×	×	×	Med	https://arpa-e.energy.gov/technologies/projects/high-performance-transistors

NO	TITLE	START DATE	END DATE	CATEGORY	CHALLENGE(S)									D-SUITE RELEVANT	LINK
					Co	M&R	PQ	ThM	CS	S&C	Su	Po	Pe		
P45	Unified Power Flow Controller	29-Sep-17	28-Sep-21	AM	✓	✓	×	×	×	✓	×	×	×	Med	https://arpa-e.energy.gov/technologies/projects/unified-power-flow-controller
P46	Titanium-Alloy Power Capacitor	09-Jan-10	30-Nov-12	AD	✓	✓	✓	×	×	×	×	×	×	Med	https://arpa-e.energy.gov/technologies/projects/titanium-alloy-power-capacitor
P47	Utility-Scale Silicon Carbide Power Transistors	09-Jan-10	31-Dec-14	AM	✓	×	✓	×	×	×	×	×	×	Med	https://arpa-e.energy.gov/technologies/projects/utility-scale-silicon-carbide-power-transistors
P48	Resonant Solid-State Breakers Based on Wireless Coupling in MVDC Systems	15-Jul-19	14-Jul-23	AM	×	✓	×	×	×	×	×	✓	×	Med	https://arpa-e.energy.gov/technologies/projects/resonant-solid-state-breakers-based-wireless-coupling-mvdc-systems
P49	Ultra-Efficient Intelligent MVDC Hybrid Circuit Breaker	09-May-19	03-Apr-23	AD	×	×	×	×	×	×	×	✓	×	Med	https://arpa-e.energy.gov/technologies/projects/ultra-efficient-intelligent-mvdc-hybrid-circuit-breaker

NO	TITLE	START DATE	END DATE	CATEGORY	CHALLENGE(S)									D-SUITE RELEVANT	LINK
					Co	M&R	PQ	ThM	CS	S&C	Su	Po	Pe		
P50	EDISON - Efficient DC Interrupter with Surge Protection	23-Sep-19	22-Mar-23	AD	×	✓	✓	×	×	✓	×	✓	×	Med	https://arpa-e.energy.gov/technologies/projects/edison-efficient-dc-interrupter-surge-protection
P51	Transformerless Converter Topology	17-Jan-18	16-Jul-22	WBG	✓	✓	✓	×	×	×	×	×	×	Med	https://arpa-e.energy.gov/technologies/projects/transformerless-converter-topology
P52	PICo-Design: Protection-Inverter Co-Design for 100% Renewable Power Systems	17-Jan-18	16-Jul-22	AD	✓	✓	✓	×	×	×	✓	✓	×	Med	https://arpa-e.energy.gov/technologies/projects/pico-design-protection-inverter-co-design-100-renewable-power-systems
P53	Distributed Energy Resource Networks	30-Sep-22	29-Sep-25	CC	✓	×	✓	×	×	✓	×	×	×	High	https://arpa-e.energy.gov/technologies/projects/distributed-energy-resource-networks

NO	TITLE	START DATE	END DATE	CATEGORY	CHALLENGE(S)									D-SUITE RELEVANT	LINK
					Co	M&R	PQ	ThM	CS	S&C	Su	Po	Pe		
P54	Substation in a Cable for Adaptable, Low-cost Electrical Distribution (SCALED)	27-Jul-16	30-Jun-22	AD	✓	✗	✓	✗	✗	✗	✗	✗	✗	Med	https://arpa-e.energy.gov/technologies/projects/substation-cable-adaptable-low-cost-electrical-distribution-scaled

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Contact Details

EMAIL

a.moon@spenergynetworks.co.uk

POSTAL ADDRESS

Andrew Moon,
Future Networks,
SP Energy Networks,
3 Prenton Way,
Prenton,
Wirral
CH43 3ET

AUTHORSHIP

Report prepared by Matthew Deakin, Jummah Abdulwali, Claire James, Chaudhry Jibran Javaid (Newcastle University, e: matthew.deakin@newcastle.ac.uk).