Hybrid Provision of Energy based on Reliability and Resiliency by Integration of Dc Equipment

Work Package WP2

Definition of Requirements, Use cases and Specification

Deliverable D2.1

Infrastructure Requirements and DC Grid KPI Definition

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List of Abbreviations

AC	Alternating Current
ACDC	Alternating Current and Direct Current
AFE	Active Front-End
BESS	Battery Energy Storage System
CIGRE	Council on Large Electric Systems
CVaR	Conditional Value at Risk
DC	Direct Current
DER	Decentralized Energy Resources
DESL	Distributed Electrical Systems Laboratory
DFG	Deutsche Forschungsgemeinschaft
DG	Distributed Generators
DoA	Description of Action
DSO	Distribution System Operator
EROI	Energy Return On (Energy) Invested
ESS	Energy Storage System
EV	Electric Vehicle
EVA	Enhanced Voltage Assessment
FPL	Flexible Power Link
HV	High-Voltage
HVDC	High-Voltage Direct Current
ICT	Information and Communications Technology
IRR	Internal Rate of Return
KPI	Key Performance Indicators
LCN	Low Carbon Network
LV	Low-Voltage
LVAC	Low-Voltage Alternating Current
LVDC	Low-Voltage Direct Current
MV	Medium-Voltage
MVAC	Medium-Voltage Alternating Current
MVDC	Medium-Voltage Direct Current
NPV	Net Present Value
PEL	Power Electronics Laboratory
PCC	Point of Common Coupling
PI	Performance Index
PV	Photovoltaics
RES	Renewable Energy Sources
RMS	Root Mean Square
ROI	Return On Investment
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control and Data Acquisition
SiC	Silicon Carbide
SVO	System Voltage Optimisation
THD	Total Harmonic Distortion
TSO	Transmission System Operator
V2G	vehicle To Grid
VaR	Value at Risk
WT	Wind Turbine

Executive Summary

This report provides insight in the planned enabling solutions to be developed within HYPERRIDE project. The infrastructure requirements, demonstration site descriptions and definition of Key Performance Indicators (KPI) outlined here have to be read in context with the connected deliverables D2.2 and D2.3.

Based on the availability of Direct Current (DC) based renewable energy resources and power electronics converters it is a possible development to evolve from currently used Alternating Current (AC) technologies to DC grid systems. Some of the benefits are:

- improved grid resiliency
- decreased cost and increased energy efficiency on system level
- facilitated integration of renewable energy sources and DC based loads
- increased transmission capacity
- reduced voltage fluctuations
- reduced control and synchronisation effort
- environmental benefits

Throughout the last decade, DC systems have been demonstrated for various use cases and rising number of pilot installations all over the world. In the report a description of the most notable installations can be found. A majority of theses demonstrators have been established in Asia. With the analysis of these instalments was possible to identify potential gaps for new infrastructures from interoperability demands in Information and Communications Technology (ICT) solutions, means of failure mitigation and prevention, mechanisms of safety such as breakers etc. The solutions in HYPERRIDE as described in D2.3 will be demonstrated in the pilot sites in Germany, Switzerland and Italy as described in the report.

To provide a toolbox for the analysis of the individual infrastructures a set of KPIs have been defined based on the methodology to evolve from available AC definitions proven to be beneficial and adapt those, if applicable, to DC grid infrastructures. In case a gap has been identified new definitions are proposed.

1 Introduction

1.1 Purpose and Scope of the Document

According to the Description of Action (DoA) (*HYPERRIDE Description of Action*, 2020), this report will focus on infrastructure requirements and KPI. With a due date of M6 in the project life cycle this report puts its emphasis on state-of-the art knowledge with respect to already existing infrastructures, the estimated developments taking place in the project at the demonstration sites (Aachen, Lausanne, Terni) and a first draft of potential KPIs suitable for DC and hybrid Alternating Current and Direct Current (ACDC) grids.

This deliverable leverages on two other deliverables which provide the broader context of the described infrastructures (see Figure 1):

- D2.2: Use case specification - a system architecture description followed by a collection of use cases for the pilot installations in HYPERRIDE and relevant technologies such as ICT solutions and components (converters, breakers, measurement units) (*HYPERRIDE Deliverable D2.2 Use Case Description, Specification and Implementation Roadmap report*, 2021).
- D2.3: Enabling technologies requirements and specification report - a detailed description of enabling technologies developed in HYPERRIDE (*HYPERRIDE Deliverable D2.3 Enabling Technologies Requirements and Specification Report*, 2021).

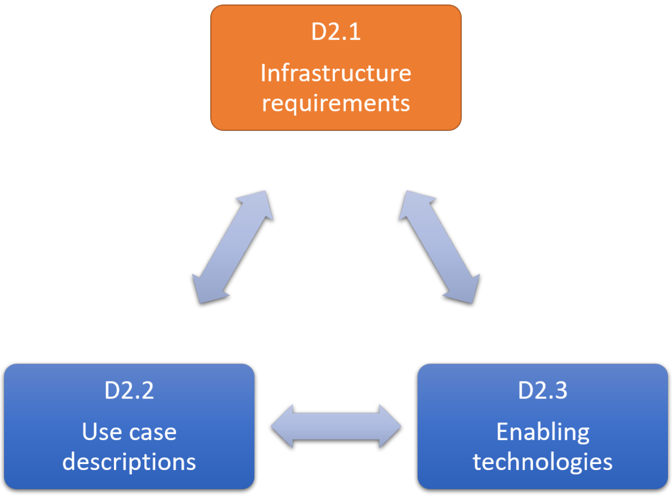


Figure 1: D2.1 in the context of other deliverables in WP2.

1.2 Structure of the Document

From system to component level, the technologies are clustered and organised in this document as follow:

Section 1 provides information about the report content.

In Section 2, the general motivation and drivers for DC infrastructure are discussed. Existing pilot installations are briefly presented and referenced. Further, the subsequently identified obstacles and resulting research questions to be addressed within the HYPERRIDE project are summarised. Finally, the HYPERRIDE pilot installations are presented.

Section 3 provides a set of KPIs suitable for the proposed infrastructures for a set of different domains. Technical KPIs focusing mainly on technical aspects of planning and operation and can be quantified directly using grid measurements. Environmental KPIs are designed to assess environmental benefits such as CO_2 savings. To assess economic aspects of the infrastructures economic KPIs are defined to provide indicators for costs and business case effectiveness. Residents, customers and consumers are mainly targeted with the definition of social KPIs to asess the social impact in the region of implementation. Finally, legal KPIs try to measure the efficiency of a legal framework

The deliverable is concluded in Section 4.

2 Infrastructure

2.1 General Motivation and Drivers for DC Infrastructure

Direct Current (DC) has several well-known advantages over Alternating Current (AC), but since DC transformation was only made possible by the introduction of semiconductors, AC had won the War of Currents in the late 19^{th} century. Nowadays, DC can be efficiently transformed using converters; the advantages of DC stay, while the biggest disadvantage disappeared. The question whether AC or DC is the better choice newly arises, for already existing as well as new power transmission and distribution installations (Hammerstrom, 2007).

International decarbonisation goals are the main driver for the high increase in Decentralized Energy Resources (DER), Renewable Energy Sources (RES), Energy Storage System (ESS) as well as Electric Vehicle (EV) and other new loads in homes and businesses. Their integration in in our energy supply system is leading towards new challenges in the low- and medium-voltage grid. The majority of these loads, storage systems and renewable energy generation units are internally operated in DC. Considering the advantages of DC for energy transmission such as increased transmission capacity, reduced conduction losses and voltage fluctuations or the facilitation of synchronisation, the introduction of DC in all grid voltage levels must be considered for secure and efficient electricity supply in the future. Furthermore, DC enables a more efficient way of integrating the increasing share of DC loads and generation units in the distribution grid thanks to the reduction of conversion stages (Dastgeer, Gelani, Anees, Paracha, & Kalam, 2019), (Siraj & Khan, 2020). In summary, the main advantages of DC distribution systems include:

- increased transmission capacity
- increased supply radii (reduced conduction losses)
- reduced voltage fluctuations
- efficient integration of DC loads and generation (reduction of conversion stages)
- optimal power flow control and short circuit current limitation
- direct energy feedback in the grid by frequency-controlled loads with DC-intermediate circuit
- reduced control variables in microgrid operation (no grid frequency/phase angle), facilitated synchronisation
- environmental benefits (e.g. reduced CO_2 emission)
- economical benefits for already existing and potential use cases/pilot installations and grid configurations
- grid resiliency (fault mitigation and avoidance of cascade effects)

Following the development of High-Voltage Direct Current (HVDC) electric power transmission systems, there are efforts to use DC at lower voltage levels. Significant developments can be observed in the field of hybrid electric propulsion (*IMOTHEP | Home*, 2020), marine systems (S. Kim, Kim, & Dujic, 2020) or data centres (Shrestha et al., 2018).

DC-based low and medium-voltage distribution networks are now being investigated in many ongoing projects and studies as, among others, explored in (Priebe et al., 2019), (Bathurst, Hwang, & Tejwani, 2015), (Lassila, Kaipia, Haakana, Partanen, & Koivuranta, 2009) and (Caujolle et al., 2019). DC micro-, Low-Voltage (LV) and Medium-Voltage (MV) grids as well as hybrid ACDC distribution grids are promising solutions for future grid scenarios, especially considering the expected technological advances in DC equipment and components. Standardisation is expected to be implemented in the next few years on an international scale. The HYPERRIDE project addresses the potential of DC and hybrid ACDC systems.

2.1.1 General Requirements on DC as an Alternative to AC

As for the KPI domains presented in the previous chapter, technical, environmental, economical, social and legal requirements must be fulfilled for DC installations to be operated in the public grid. In general, these requirements do not differ for AC or DC systems from a customer point of view. They include high level requirements such as:

- Reliability
- Economical benefits
- Environmentally friendly
- Safe and Secure operation
- Interoperability of components and systems

It must be ensured that DC installations are capable of at least fulfilling all requirements defined and set over the past century for AC grids. Additionally, DC specific requirements must be considered. Moreover, new challenges and requirements coupled with the hybridisation of the electric grid arise. The main differences between AC and DC must be identified and addressed in extended standardisation. Further requirements must be defined from a grid operator perspective to fulfil the high level customer requirements:

- Interconnectivity with existing grid (transition from AC to hybrid ACDC)
- Flexible and attractive pricing models
- Renewable and local energy generation
- Integration of local energy communities
- Low environmental impacts such as CO_2 emission
- Standardisation

Within the HYPERRIDE project, the deliverable **D2.3 Enabling technologies requirements and specification report** gives a more specific overview of the DC system requirements.

2.1.2 Refurbishment of Existing Grids and Requirements

Beside the potential benefits of DC systems in newly installed distribution systems, significant improvements in already existing infrastructure can be achieved by refurbishment of existing AC grids and lines to be operated in DC. Refurbishing existing AC distribution cables to operate under DC conditions can offer several advantages in terms of capacity enhancement, efficiency and flexibility in power and voltage control, among others (Shekhar, Kontos, Mor, Ramírez-Elizondo, & Bauer, 2016). Especially where the existing AC grid reaches its limitations, the conversion of selected lines or feeders to DC can be economically and environmentally beneficial. The modification of an AC to a (partly) DC system can eliminate the need for construction, replacement or reinforcement of lines, cable sections, power transformer etc. Pilot projects show how conversion of existing lines to DC can be economically beneficial, as presented in Section 2.2.1, or that the refurbishment of an AC line allows the continuous usage of a partially damaged cable due to single-phase failure by converting the system to bipolar DC operation, as discussed in section Section 2.2.9.

2.2 Examples of Existing DC Pilot Installations Outside HYPERRIDE

In the following section, some of the most relevant Low-Voltage Direct Current (LVDC), Medium-Voltage Direct Current (MVDC) and hybrid AC/DC pilot installations are briefly presented and referenced. In (Fan et al., 2021) a more detailed analysis on some of the below mentioned pilot installations and their key technologies can be found.

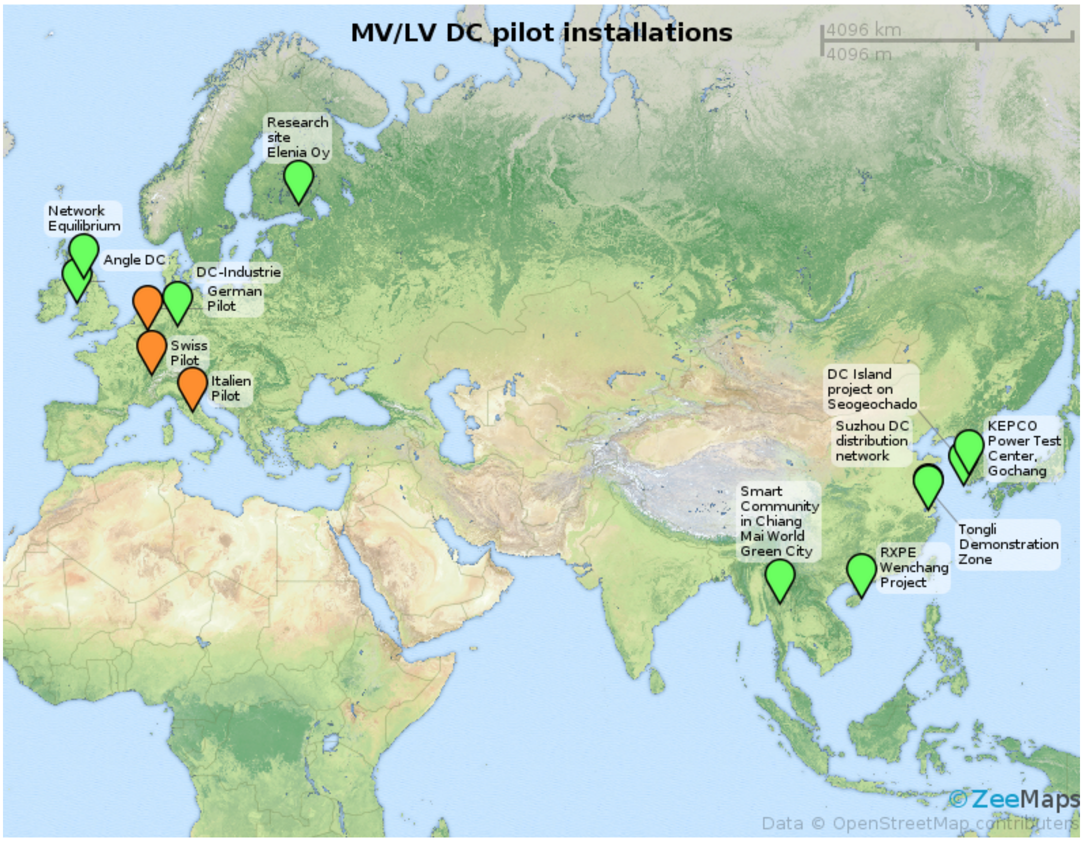


Figure 2: Green: Pilot installations outside HYPERRIDE, Orange: HYPERRIDE pilot installations.

2.2.1 Elenia Oy Research Site, Finland

Actors: LUT University, local Distribution System Operator (DSO) (Järvi-Suomen Energia Oy), rural residents, national regulator, owner (energy corporation Suur-Savon Sähkö Oy)

Status: in operation since 2012

References: (Lana, Nuutinen, et al., 2015), (Lana, Pinomaa, Nuutinen, Kaipia, & Partanen, 2015), (Nuutinen et al., 2014), (Nuutinen et al., 2013), (Kaipia et al., 2012), (Nuutinen et al., 2011)

Key facts and motivation

Research site for a LVDC distribution system. The restructuration of long MVAC branch overhead-lines/cables to LVDC was set up to optimise costs and reduce grid outages (can be several hours to days due to summer- and winter storms). In the 2nd project phase, a battery storage (Li-Ions, 60 kWh) was included directly in the DC-intermediate circuit of the bidirectional rectifier. The system allows alternative LVDC or LVAC (20 kV/1 kV, 1 kV/0,4 kV) power supply. At the customer end, inverters convert the electric energy back to AC (rural residents). Due to penalty payments for DSOs if limits for grid outage time is exceeded for rural/urban area (national regulator), the cost effectiveness of the LVDC system is high. In the 3rd phase of the project, a PV-installation (RES) was included in the DC circuit. The LVDC system brings benefits for increased hosting capacity, voltage quality (voltage drop) and power supply range.

Options: energy communities with microgrids (partial energy market integration), partially isolated/off-grid operation from main grid, providing ancillary services for external market actors (e.g. storage usage).

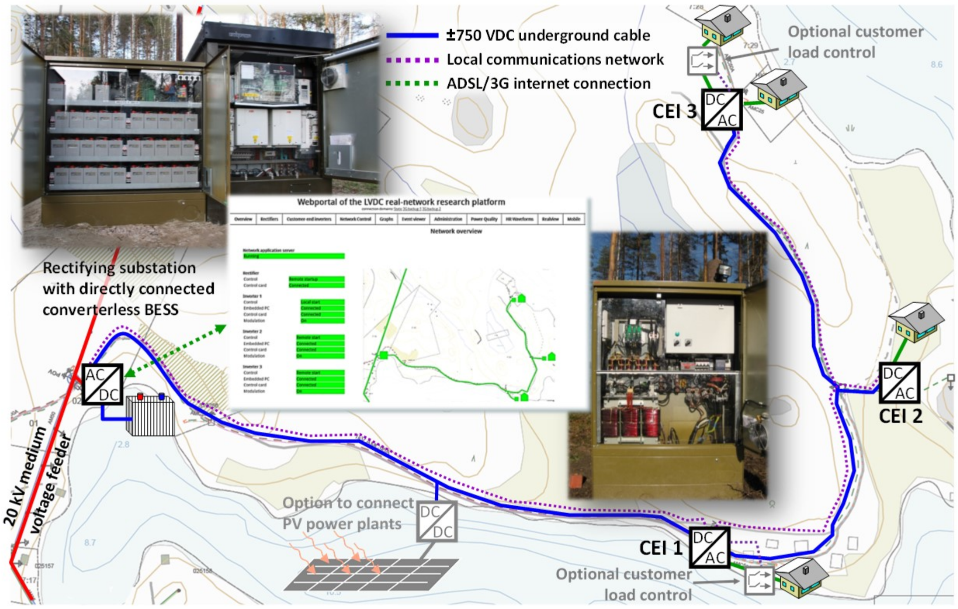


Figure 3: LVDC on „last mile“ (after MVAC/LVAC transformer, isolated-operated +/-750V LVDC grid). The LVDC network is in constant use and supplies electricity for the daily needs of four residential customers.

2.2.2 Gochang Power Test Center, South Korea

Actors: Korea Electric Power Corporation (KEPCO)

Status: in operation since October 2016

References: (Afamefuna, Chung, Hur, Kim, & Cho, 2014) (J. Cho, Kim, Chae, Lee, & Kim, 2015), (Y. Cho, Kim, Kim, Cho, & Juyong, 2017), (J. Kim, Kim, Cho, Kim, & Cho, 2019)

Key facts and motivation

LVDC distribution Demo Project in South Korea. It is claimed to be the largest in the world, with 6 km of overhead line and underground cables. The centre is equipped with a 500-kW

AC-DC power converter, a 2-MW ESS, 250-kW wind turbines, 250-kW Photovoltaics (PV)s, 50-kW vehicle To Grid (V2G), a 100-kW diesel generator, 100-kW co-generation facilities, 600-kW artificial load, DC home appliances (for example, refrigerators, computers and TVs), high-speed DC circuit breakers and operating systems.

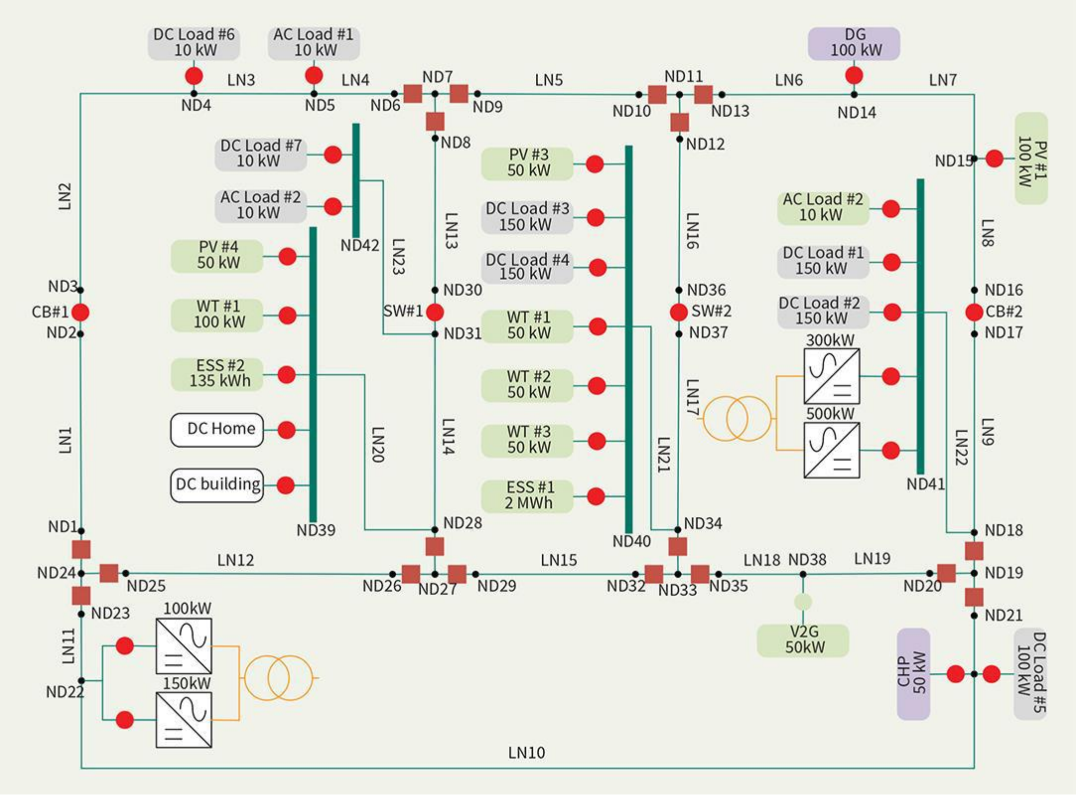


Figure 4: KEPCOs Gochang Power Test Center pilot.

The LVDC distribution overhead line is an existing 22.9 kV circuit from Mangwol, South Korea, to Cheongokjji, South Korea: The ±750V ungrounded-type overhead line consists of a 75-sq-mm (0.17-sq-inch) cable, a 30-kW rectifier, a 30-kW inverter and an operating system. The rectifier input group consists of a single-phase 22.9 kV, 220 V pole-mounted AC transformer. In addition, the LVDC line has a line cutoff switch (COS), load pole-mounted transformer and AC switchgear installed for protection in the event of a fault on the LVDC distribution line.

2.2.3 DC Island Project on Seogeochado (West Geocha Island), South Korea

Actors: Korea Electric Power Corporation (KEPCO), Smart Power Distribution Laboratory KEPRI (KEPCO Research Institute), residential customers

Status: in operation since September 2018.

References: (H. Kim, Cho, Kim, Cho, & Juyong, 2017), (J. Cho, Kim, Cho, Kim, & Kim, 2019), (Juyong et al., 2020)

Key facts and motivation

In Seogeochado, KEPCO constructed a 1500 V_{DC} (±750 V_{DC}) distribution line to replace an existing 6.6 kV_{AC} distribution line. KECPO DC Island project aims to demonstrate an independent DC microgrid system, prove the efficiency of a DC system, and to establish a track record for commercialization. DC Island designed a complete DC system, from diesel generation and renewable sources such as PV, ESS and Wind Turbine (WT), to loads.

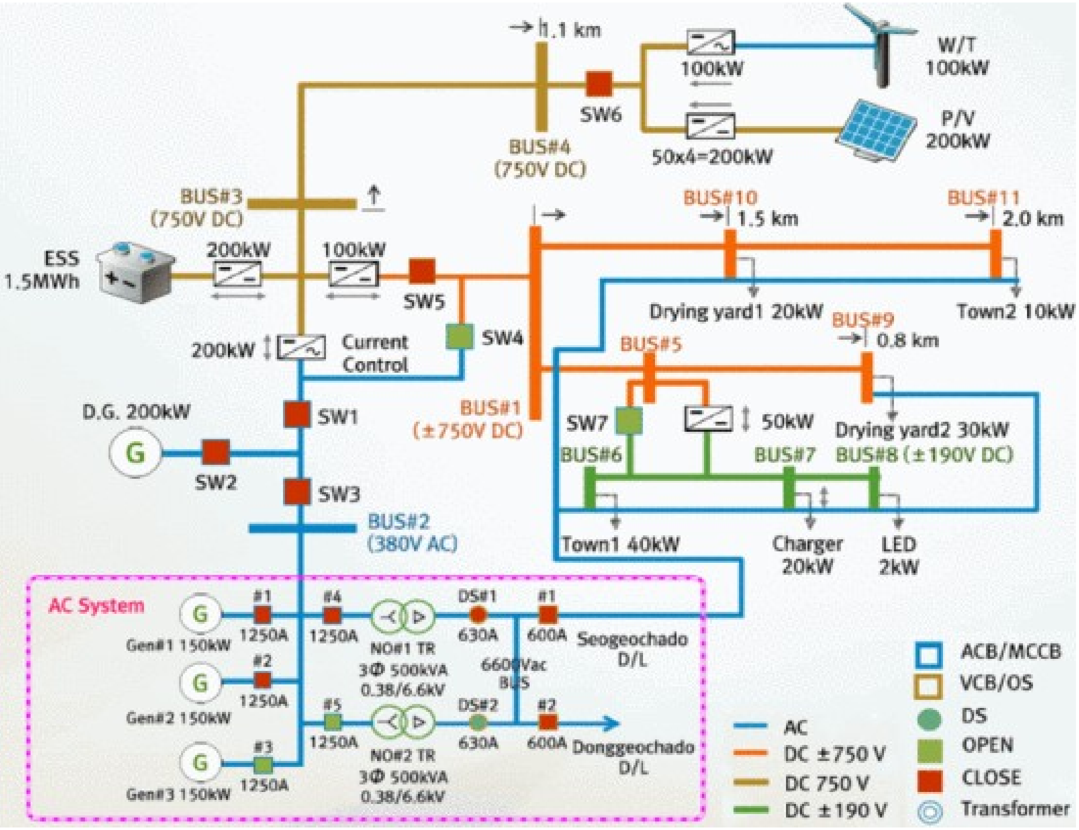


Figure 5: Seogeochado DC microgrid system network diagram.

Hybrid LV ACDC distribution Demo Project has voltage values equal to +-750 V_{DC}, 750 V_{DC}, +-190 V_{DC} buses (and 380 V_{AC} bus). This LVDC project included the installation of 100 kW Wind turbine, 50x4=200 kW PV, 1,5 MWh/200 kW Battery Energy Storage System (BESS), 200, 200 kW rectifier to supply DC-bus/DC loads (EV charging point 20kW LED 2 kW), new 200 kW diesel generator, 450 kW conventional generation and DC electric charging points for EVs.

Overall, KEPCO aimed to improve the energy efficiency of the island by 10%.

2.2.4 Tongli Demonstration Zone, Suzhou Renewable Energy Town, China

Actors: Jiangsu Provincial Government, State Grid Cooperation of China, Tonglihu DC area, Mingzhi Technology PV area; Supported by 2017-2020 National key research project "ACDC hybrid renewable energy technology based on power electronic transformer"

Status: in operation since October 2018

References: (*Suzhou Eco-Town*, n.d.), (Han et al., 2019)

Key facts and motivation

The key goals of this pilot are the following:

1) To improve the renewable energy consumption capacity of public power grid. Tongli belongs to the industrial developed towns just along the Yangtze River. Distributed PVs are installed on the roofs of many industrial factories to reduce power consumption which comes up with a lot of over voltage in Point of Common Coupling (PCC) and therefore a lot of solar energy should be abandoned.

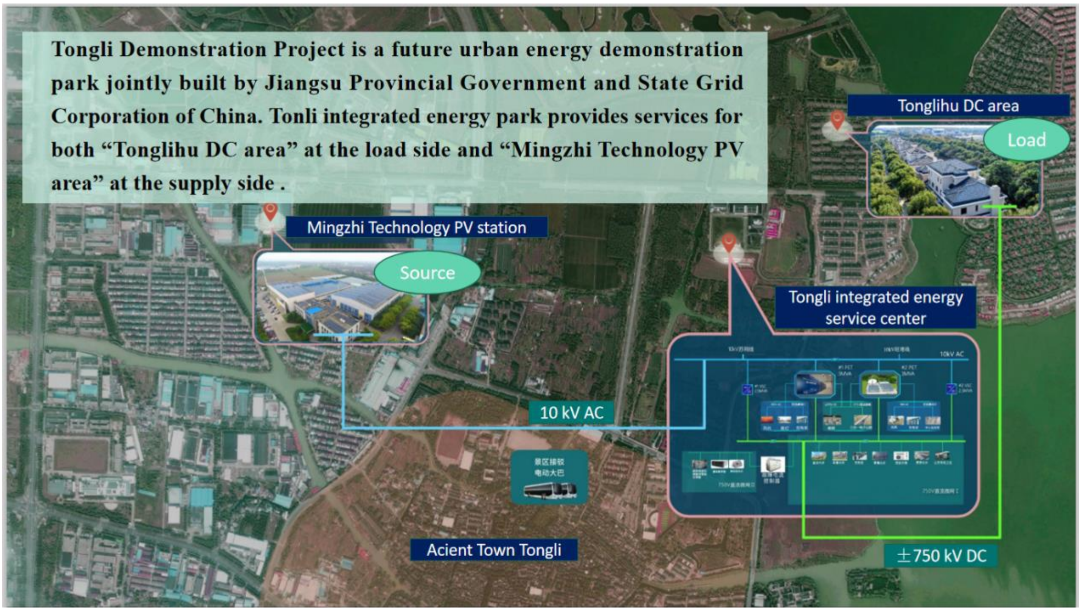
2) To supply power in high efficiency. Tongli lake, as a 5A scenic spot, pays a lot attention to the environmental friendly technology. With the integration of DC systems, the power efficiency is improved significantly

3) To explore energy transformation technologies (DC Fault Current controller (technology?), PET 10k V$_{AC}$ / 380 V$_{AC}$ / +-750 V$_{DC}$, +-375 V$_{DC}$ (3MW Si, 3x1MW Silicon Carbide (SiC)), Multi-boundary Protection Based on DC Grid Topology (GOOSE high-speed real-time communication technology realizes the rapid identification and precise faults excising), Impedance-based low frequency oscillation analysis and parameter optimization, single point grounding via anti-parallel diodes.

4) Increased personal safety (LVDC instead MVAC)

5) Power Quality: Without reactive power loss and skin effect, voltage drop is reduced. The energy storage solves the problem of voltage flicker.

6) Household interfaces: DC converter is smaller and can be integrated into household appliances. The power adapter can be simplified or even omitted.



Tongli Demonstration Project is a future urban energy demonstration park jointly built by Jiangsu Provincial Government and State Grid Corporation of China. Tonli integrated energy park provides services for both "Tonglihu DC area" at the load side and "Mingzhi Technology PV area" at the supply side .

Figure 6: Multi-type distributed renewable energy source of 2.956 MW and DC load of 1.8 MW in Tongli Demonstration Zone, SUZHOU.

2.2.5 Suzhou DC Distribution Network, China

Actors: 2018 National key research and development projects

Status: in operation

References: (Liang, Mengmeng, Qiang, Xiaodong, Gu, & Fei, 2018), (Liang, Mengmeng, Qiang, Xiaodong, & Fei, 2018), (Wu et al., 2019)

Key facts and motivation

The Suzhou DC distribution network is a typical MVDC project with multiple voltage levels and multiple application scenarios, sponsored by 2018 National key research and development projects of China. This project aims to explore the power supply mode, grid structure of MVDC system, realise the DC power transmission in long distance and improve the reliability of power supply and energy utilisation. A variety of key equipment of MVDC system, such as DC transformer, medium voltage DC circuit breaker and DC adapter, have been developed. Concretely, Suzhou MVDC system contains two 10 MW AC-DC converters, 4 DC circuit breakers, 82 DC load-break switches and 19 DC transformers with the capacity of 1 MW or 2 MW, which has three stage of voltage levels as ± 10k V_{DC}, ± 375 V_{DC} and ±48 V_{DC}. Besides, there is a 6.4 MW PV generator integrated and it will supply power to various kinds of loads with the capacity up to 10.7 MW, including resident load/data centre/commercial load/industry load and charging pile.

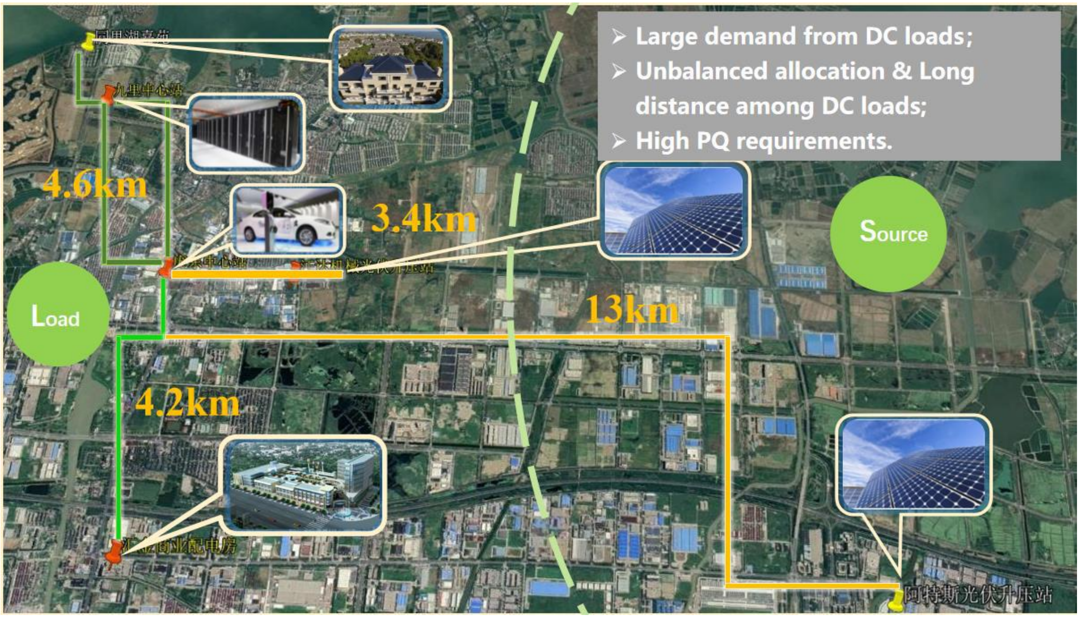


Figure 7: Medium-voltage DC distribution system demonstration project in Suzhou.

It is a big challenge to make this complex system safe, stable and economical. To take into account above objectives, different strategies and topologies are applied in consideration of different scene characteristics to make the system operate with high efficiency, high power density, high reliability and economic separately. Furthermore, in order to realize the DC adaptation of the end users, 10 kinds of household appliances such as refrigerators, washing machines, etc. are remaking, which is expected to improve the comprehensive energy efficiency of electricity consumption by 2%.

2.2.6 DC-Industrie, Germany

Actors: 39 Partners from industry and research, ZVEI (Zentralverband Elektrotechnik- und Elektronikindustrie e.V.), Energy Research Programme of German Federal Government, BMWi

Status: ongoing research project since 2016

References: (*dc-industrie.zvei.org*, n.d.), (Stammberger, 2020)

Key facts and motivation

“DC-Industrie” is a German initiative mainly based on two projects funded by Energy Research Programme of German Federal Government with a focus on energy efficiency and energy flexibility in industrial production, thus a kind of DC-based smart grid for industry. It is foreseen as a setup of a manufacture-independent LVDC system concept. Modules of in-feeds via AC-DC rectifiers for connection to the LVAC main grid, variable speed motor drives, DC-supplied machines and robots and passive DC-loads are summarised in (independent) load zones. These modules are connected by “connection-boxes” - including equipment for load zone and cable protection using fast hybrid- and solid-state LVDC circuit breakers, pre-charging and disconnection - together with PV plants and storage applications on a DC-bus (DC-backbone). The DC-network is buffered by enough intermediate-circuit capacity to keep away switching frequency-based clearing procedures from the devices in a semi-industrial environment. The industrial DC power supply includes an energy management to balance the DC-voltage - nominal 540 V_DC for uncontrolled supply on 400 V AC-grid and 650 V_{DC} for controlled supply and uncontrolled on 480 V grid - within pre-defined bands like nominal, steady-state over-/under voltage, transient over-/under voltage and switch-off limits 400 / 800 V. Advantages of this concept are increased energy-, resources- and cost efficiency and reduced space by elimination of the rectifier converter stage (applications) and grid-filter coils of variable speed drives with direct energy recovery in the DC-bus (no bidirectional rectifiers necessary), better utilisation of cable cross-sections, fault-ride through capabilities and grid support functionalities. Extension up to production halls, e.g. 400 m length, are considered.

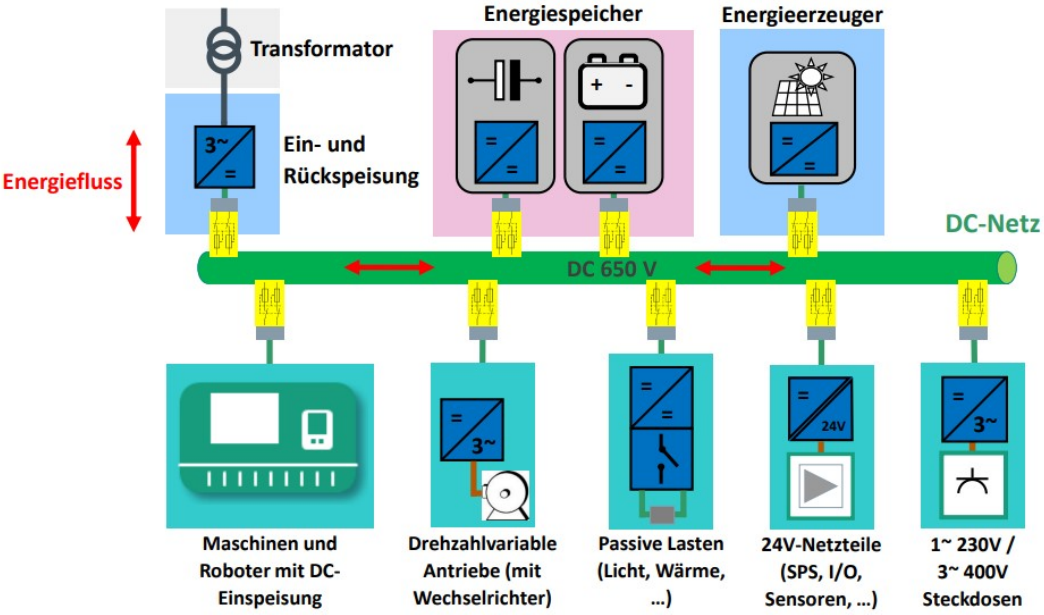


Figure 8: Vision: Topology of industrial DC factory network.

In 1st project phase DC-INDUSTRIE (2016-2019) the demonstration, evaluation and operational experience of the basic configuration for several production cells like robot cells for automotive industry” (handling, spot welding, gluing, setting of self-pierce rivets), “pneumatic drives” and a “conveying system”, including photovoltaic and storages (battery, fly-wheel, and capacitors) were in focus. The objects of ongoing 2nd project phase DC-INDUSTRIE2 (2019-2022) are safe and robust energy supply of production plants (extension to whole production halls), mains-supporting connection to the supply mains, simple project planning and maximum use of decentralized, regenerative energy generation. Prove of evidence will be done in 6 model plants and transfer centers.

2.2.7 Network Equilibrium, United Kingdom

Actors: Ofgem (national regulator), Western Power Distribution

Status: completed in June 2019

References: (*Western Power Distribution - Projects*, n.d.), (J.Berry, N.Murdoch, & Y.Mavrocostanti, n.d.)

Key facts and motivation

Network Equilibrium is a Low Carbon Network (LCN) Fund Tier 2 project. The LCN Fund was a funding mechanism introduced by Ofgem as part of the Distribution Price Control Review (DPCR) 5 price control period. Network Equilibrium was successfully awarded £13m of funding in November 2014. The project started in March 2015 and was completed in June 2019. The main aim of the project was to improve the balance of voltages and power flows across the distribution network using three methods. The development of the methods allowed new ways of configuring and managing the network to be trialled thus releasing capacity for the more efficient connection of Distributed Generators (DG). The three methods are as follows: Enhanced Voltage Assessment (EVA), System Voltage Optimisation (SVO) and Flexible Power Link (FPL).

The FPL consists of two 33 kV back-to-back AC-DC voltage source converters connected together via a DC busbar link that allows two 33 kV distribution networks to be connected in parallel through the device. The FPL as part of Network Equilibrium was connected across two previously unconnected electricity distribution networks to enable active power (P) transfer between them and provide independent reactive power (Q) on both sides. The active power flow operation of the FPL - active power is transferred from a generation dominated network in Grid Group A1 to a demand dominated network in Grid Group A2. This enables a greater utilisation of the complete system, whereby previously the Grid Group A1 would have reached its capacity of generation acceptance (due to reverse power flow and short time voltage band overshooting constraints) and significant network reinforcement would be required (new cables, power transformers). Similarly this would be the case for an increase in load on the Grid Group A2 (causing firm capacity limits to be exceeded) that could be transferred to Grid Group A1 to mitigate reinforcement requirements. This parallel configuration would not have been able to be safely achieved without the FPL due to circulating currents, protection grading and fault level issues. The FPL can actively manage the real and reactive power flow at its terminals to release network capacity and provide voltage support in both normal and abnormal network running conditions.

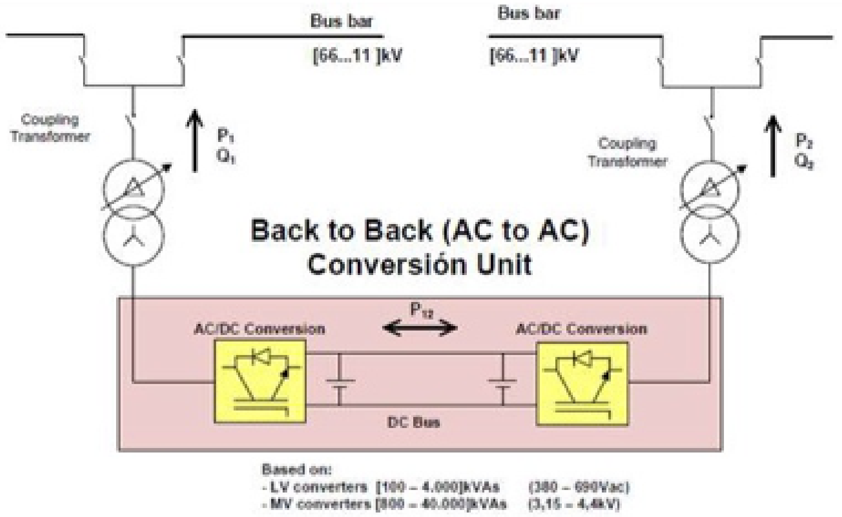


Figure 9: Flexible Power Links (FPL) within Network Equilibrium Project.

2.2.8 Angle DC, Scotland

Actors: Scottish Power Energy Networks (SPEN), Ofgem (national regulator), GE Power Conversion, Cardiff University, Welsh Government, Isle of Anglesey County Council, Western Power Distribution (WPD)

Status: in progress

References: (*Angle-DC Project Summary*, n.d.)

Key facts and motivation

Angle DC is a Network Innovation Competition (NIC) Project developed by Scottish Power Energy Networks (SPEN). It was awarded funding from the UK energy regulator, Ofgem, in 2015 and is due to be completed in April 2020. The aim of the project is to convert an existing AC double circuit 33 kV line into a symmetrical monopole MVDC link i.e. each circuit carries one of the poles +/- 27 kV$_{DC}$ in this case. The double circuit connects Lanfair PG substation on Anglesey Island with Bangor substation on the North Wales mainland. The island of Anglesey is experiencing both load and distributed generation growth in the form of renewable generation such as wind, solar and tidal. The 33 kV circuit in question is forecast to experience thermal limitations and voltage will be increasingly difficult to manage.

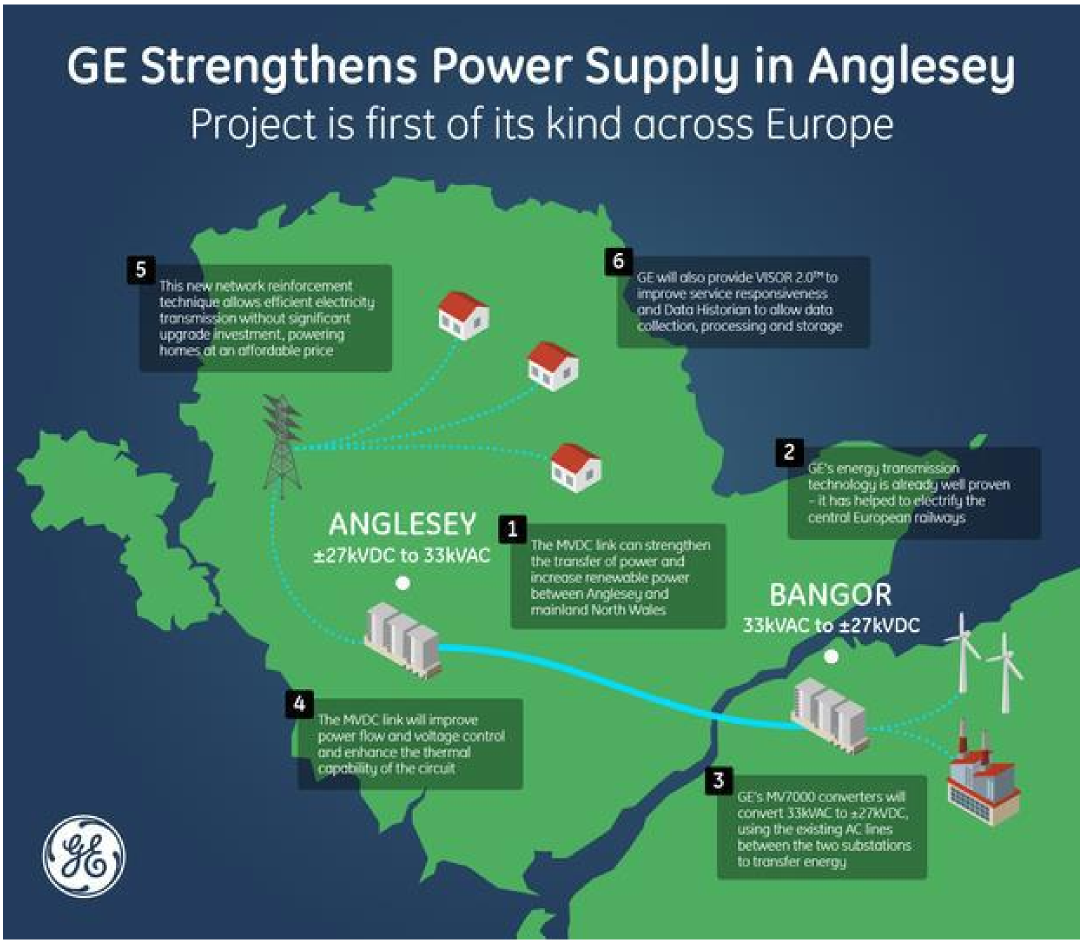


Figure 10: Angle-DC project.

It is anticipated that changing the existing AC circuits to DC operation will increase the cable nominal rating by 23% allowing for increased power flows. The MVDC link will allow greater control of the power flow through the circuit and also improve voltage management at either end of the link. The MVDC technology is being supplied by GE and for this application they are utilising 12 units of their MV7000 converters at each converter station. This product is normally used as a Variable Frequency Drive (VFD) system for MV motors and it is unknown at this stage how they will be adapted for the MVDC link application. This information will likely become known when SDRC-4 and SDRC-5 project reports are published by SPEN.

2.2.9 RXPE Wenchang Project, China

Actors: Rongxin Power Engineering (RXPE), oil industry

Status: in operation since 2013

References: (Liu, Cao, & Fu, 2017)

Key facts and motivation

Rongxin Power Engineering (RXPE) is an international developer based in China and provider of high voltage power electronic solutions that include statcom and HVDC systems. RXPE are also able to offer MVDC solutions as part of their offering. They are able to provide 5 kV-50 kV VSC MVDC systems able to transmit power up to 100km. RXPE have installed a number of MVDC systems to facilitate power supplies for offshore oil platforms. An example of one of these projects is given below.

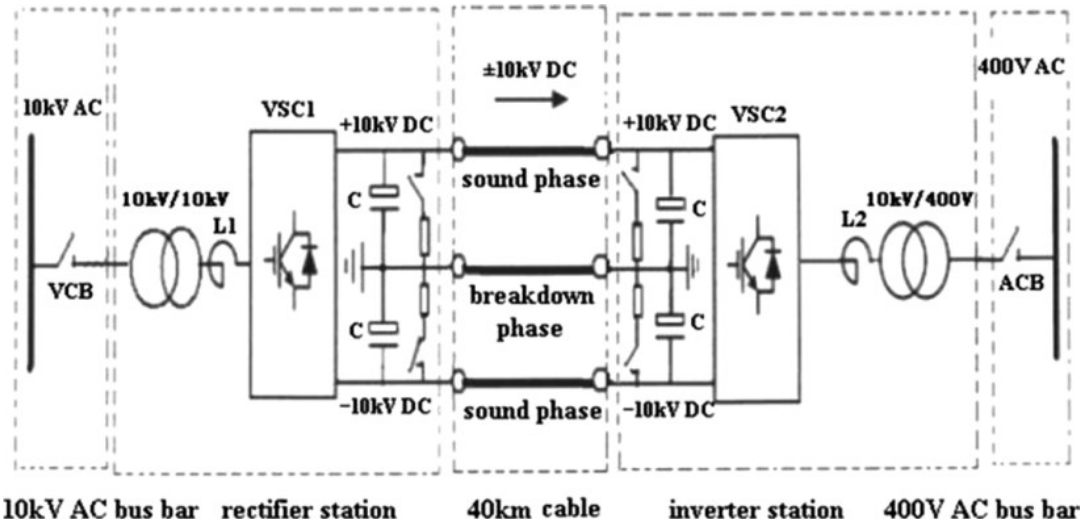


Figure 11: The DC operation scheme of the existing AC cable circuit.

An MVDC system has been provided for China National Offshore Oil Corporation (CNOOC) as part of the Wenchang platform submarine cable repair project. This was provided by the specialist power electronic equipment manufacturing RXPE on a turn-key basis. A main oil platform in the Western South China Sea was supplying a remote platform via three single phase AC sub-sea cables. One of the cables suffered an insulation failure and meant that the remote platform had to run on back-up diesel generation. An 8MVA +/-15 kV MVDC system was installed to restore the electricity supply (MVDC-Link). The system was a symmetrical bipole arrangement that utilised the healthy AC phases as the positive and negative DC cables and the faulted phase as the neutral. The MVDC solution has been operating successfully since 2013.

2.2.10 Smart Community in Chiang Mai World Green City, Thailand

Actors: Asian Development Institute for Community Economy and Technology (adiCET), Chiang Mai Rajabhat University, Office of Naval Research USA, local residents

Status: in operation since 2011

References: (Setthapun et al., 2015)

Key facts and motivation

The Smart Community is a real living model community in the mountainous area that completely uses electricity from PV and distributes with DC microgrid in the range of 260 – 297 V$_DC$.

In early 2011, the Smart Community used 240 V$_{AC}$ power completely from the university grid. Then, in late 2011, 24 V$_{DC}$ lighting systems were integrated in every building with the underground 24 V$_{DC}$ microgrid system and 25.5 kW PV source. Only the lighting were operated on DC but the rest of the electrical devices were operated with university AC power. During that time, only one house has all appliances modified and tested with 240 V$_{DC}$ for one year. After

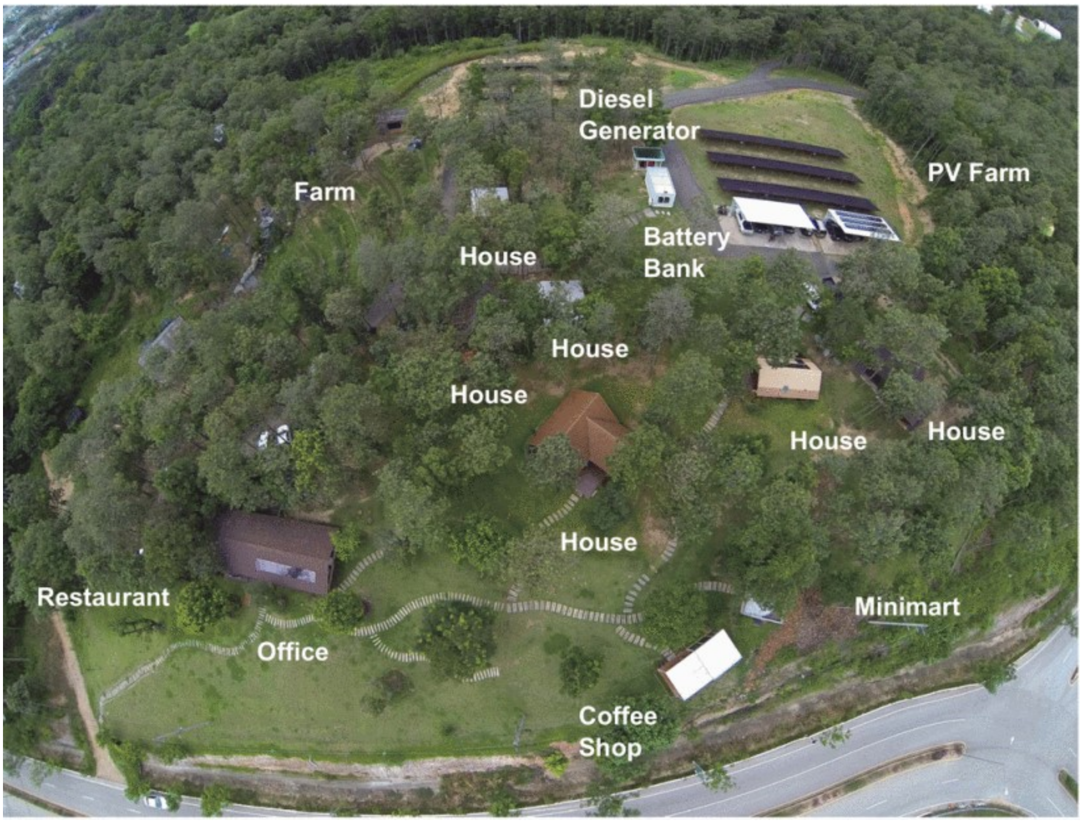


Figure 12: DC microgrid implemented in the smart community in Chiang Mai World Green City.

system optimization, in early 2013, all the building and farm of the Smart Community were modified to be able to operate on the 260 – 297 V_{DC}. In addition, the AC power from the university system was replaced with the AC power from another 25 kW PV source. The diesel generator and biomass gasification system were also integrated to the Smart Community power system making the Smart Community a true test-bed for hybrid community DC microgrid system. Therefore, the model of integrating the DC power systems to the existing AC power system in real-living community were explored as the starting point toward the transitioning to an efficient DC based society.

2.3 Obstacles and Research Questions

Based on the above discussed requirements and pilot projects, the following obstacles can be identified:

- Few existing basic studies and experimental development in the field (more specific funding instruments/budget needed). More pilot projects needed.
- Lack of standards (for components and grid codes).
- Lack of commercially available products especially for medium voltage, but also for extended low voltage DC grids.
- Lack of practice in planning and safe operation of distributed, highly dynamic DC grids with low system inertia in the event of a fault, taking into account current converter power limits at grid operators (except use cases with DC systems operated in isolation from

AC and point-to-point HVDC and MVDC links), lack of reliability studies from a system perspective.

- Lack of modular transition strategies from AC to ACDC hybrid grids.
- Key technologies for DC components and systems still need to be developed to higher TRL 5-9.
- Lack of automation and ICT concepts for DC grids.
- Interoperability (and cyber security) must be ensured for multi-terminal and multi-vendor applications for distribution grids.
- Lack of testing infrastructure and testing methods for DC components and system testing (especially towards higher MVDC voltages, but also LVDC).

Combining requirements, obstacles and already existing knowledge within the industry, the resulting research questions will be addressed within the HYPERRIDE project and its pilot installations:

- Which practical challenges arise with the implementation of DC infrastructure?
- How can currently missing standards for components and grid codes be formulated to ensure product interoperability for DC systems?
- How can stability be guaranteed in DC and hybrid ACDC networks?
- How can efficiency and sustainability be increased from a system perspective?
- How can resource sustainability be increased through DC technologies?
- How can a modular transition strategy from AC to ACDC hybrid grids look like?
- What is the impact on overall system reliability of using DC technologies?
- How can DC technologies be used to increase the resilience of distribution networks?
- What are the effects on component ageing of operation with DC voltage and future high-frequency pulsed converters?
- How will future-proof automation and ICT concepts for DC grids look like?
- How will test infrastructure and test methods for DC components and system tests look like?

2.4 Installations in HYPERRIDE

2.4.1 Aachen (Germany)

Geographical location

RWTH Aachen University is located in Aachen, North Rhine-Westphalia (NRW), Germany and it is a public state university. Aachen, also know as Bad Aachen, in French (and formerly in English) as Aix-la-Chapelle, is a spa and border city in North Rhine-Westphalia, Germany. Aachen developed from a Roman settlement and spa, subsequently becoming the preferred medieval Imperial residence of Emperor Charlemagne of the Frankish Empire, and, from 936 to 1531, the place where 31 Holy Roman Emperors were crowned Kings of the Germans. Aachen is the westernmost city in Germany, located near the borders with Belgium and the Netherlands, 61 km (38 mi) west of Cologne in a former coal-mining area as shown in 13. One of Germany's leading institutes of higher education in technology, the RWTH Aachen University, is located in the city. Aachen's industries include science, engineering and information technology. In 2009, Aachen was ranked eighth among cities in Germany for innovation.

Figure 13: German pilot location.

Area details

RWTH Aachen is a public research university located in Aachen, North Rhine-Westphalia, Germany. With more than 45,000 students enrolled in 144 study programs, it is the largest technical university in Germany. In 2011, the university accounted for the highest amount of third-party funds of all German universities in both absolute and relative terms per faculty member. In 2007, RWTH Aachen was chosen by the Deutsche Forschungsgemeinschaft (DFG) as one of nine German Universities of excellence for its future concept RWTH 2020: meeting global challenges and additionally won funding for one graduate school and three clusters of excellence. RWTH Aachen is a founding member of IDEA League, a strategic alliance of five leading universities of technology in Europe.

RWTH Aachen University's 620 acres (250 ha) campus is located in the north-western part of the city Aachen. There are two core areas – midtown and Melaten district. The Main Building, SuperC student's center and the Kármán Hall are 500 m away from the city centre with the Aachen Cathedral, the Audimax (biggest lecture hall) and the main refectory are 200 m farther. Other points of interest include the university's botanical garden (Botanischer Garten Aachen).

A new building, the so-called Central Auditorium for Research and Learning (CARL) was opened in 2017. It offers space for 4000 students and replaces Audimax as the largest lecture hall building. The name of the new central auditorium, which is going to contain different lecture halls, is a reference to Charlemagne, who reigned his empire from Aachen in the middle-ages.

The RWTH has external facilities in Jülich and Essen and owns, together with the University of Stuttgart, a house in Kleinwalsertal in the Austrian Alps. The university is currently expanding in the city center and Melaten district. The SuperC, the new central service building for students, was opened in 2008. The groundbreaking for the new Campus-Melaten was in 2009.

Currently 16 research clusters including Sustainable Energy Cluster are under development on RWTH Aachen Campus in close proximity to major research institutes and facilities. The objective of the Sustainable Energy Cluster is increased energy efficiency and a switchover to sustainable energy generation. One of the key methods applied is the interconnection of the various energy networks (electricity, gas and heat) with decentralized infeeds. This method is known as “smart grid” (for electricity).

Resource-friendly energy generation is explored in terms of need, economy and social aspects. In terms of technology, research is directed at the various basic disciplines, e.g. in terms of a) new materials for thermal insulation in intelligent facades or b) new semiconductor structures for energy conversion technology (power electronics, phase change materials)

The following centers form the key research areas in the Sustainable Energy Cluster:

- BMBF Research Campus Flexible Elektrische Netze (Flexible Electrical Networks)
- E.ON Energy Research Center

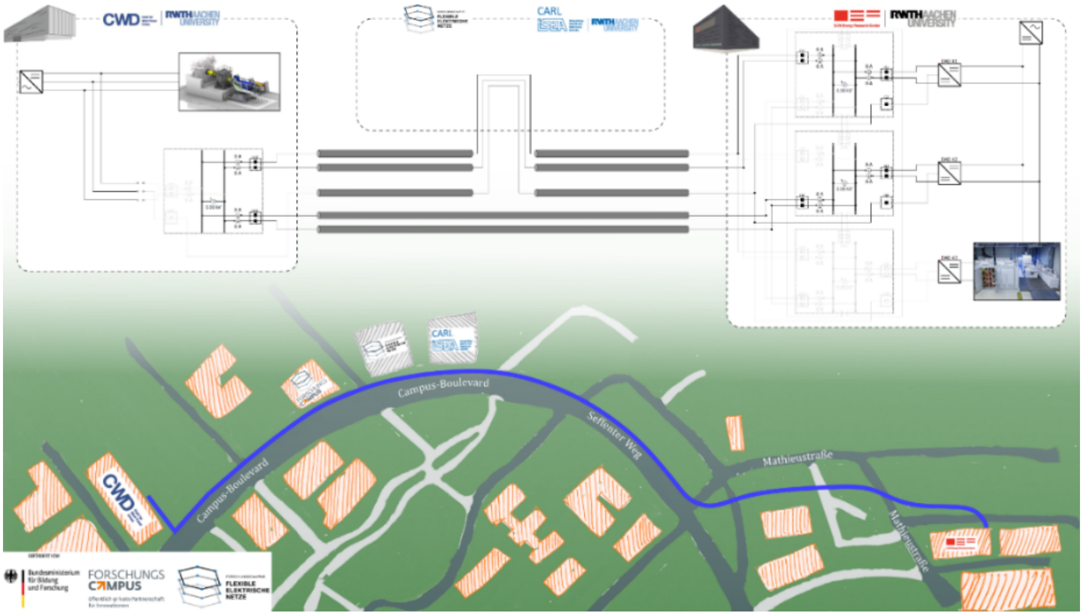


Figure 14: Interface 5 kV MVDC grid of the German demo-site.

Key facts

The German demo-site is located at the RWTH-Aachen Campus Melaten in Germany and consists of 5 km MVDC cables connecting three different locations as shown in 14. The grid is operated by the Institute for Power Generation and Storage Systems (RWTH-PGS) together with other partners of the Research Campus Flexible Electrical Networks. In addition, RWTH-

PGS offers a large portfolio of high-power DC-DC and DC-AC converters that can be used to form hybrid ACDC grid structures.

Infrastructure facts

The German demo-site, as depicted in 15 is based on available infrastructure and converter technologies developed in previous projects. This demo-site offers a modular design, easily re-configurable to test different network architectures. It integrates two MVAC grid connections, which are supplied by different grid operators. The first MVAC connection is linked to the RWTH University 10 kV$_{AC}$ grid and supplies a high-speed drive test bench including a 5 kV DC-DC converter. This converter can link the high-speed drive test bench to the Center for Wind power Drives (CWD) of RWTH Aachen University, where a 4 MW wind turbine test bench is located. The second MVAC connection is achieved at CWD using an Active Front-End (AFE) converter. A local grid operator (Regionetz) feeds this MV grid connection. The available converters offer the following possibilities of grid interconnections.

- MVAC/MVDC interconnections: 3.3 kV$_{AC}$ / 5.0 kV$_{DC}$
- MVDC/MVDC interconnections: 5 kV$_{DC}$ / 5 kV$_{DC}$ (galvanic isolation)
- LVAC/LVDC interconnections: 400 V$_{AC}$ / 750 V$_{DC}$ (galvanic isolation)
- MVDC/LVDC interconnections: 5 kV$_{DC}$ / 750 V$_{DC}$ (galvanic isolation)

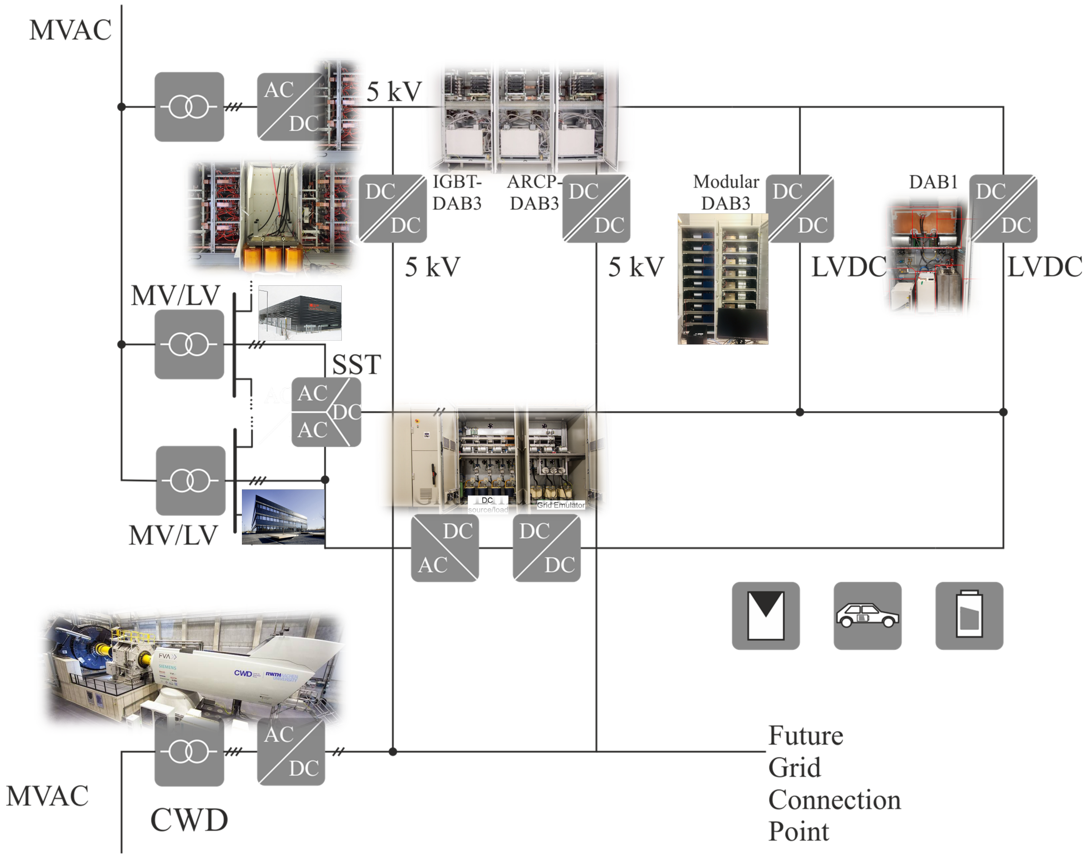


Figure 15: Grid topology of the German demo-site.

2.4.2 Lausanne (Switzerland)

Geographical location

Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland is one of the youngest institutes of technology in the world with over 16000 students and collaborators. Located at the Léman lake, EPFL campus is an attractive place with well-developed infrastructure, supporting the research activities in over 370 laboratories, spread over the various research areas and domains (Figure 16). Due to favourable geographic conditions, energy landscape of Switzerland is largely dominated by the hydropower sector which is providing near 60% of country energy needs. Nuclear energy generation amounts to near 35%, with planned phase out in incoming years. Relatively modest, but slowly increasing percentage of electrical energy comes from the photovoltaic and wind generation. Considering the size of the Switzerland, complete electrical network is AC from 110 kV on the transmission level, down to typically 20 kV on the distribution level. There are no DC installations or DC links used in any part of the electrical network.

Figure 16: Overview of the Swiss demo-site.

Area details

Lausanne and thus EPFL campus are located in the region managed and operated by the local DSO Romande Energie. Even though EPFL and campus are public property, various demonstration projects involving local DSO have been organised in the past or are ongoing. Relevant for the HYPERRIDE project are the research activities related to the electrical energy domain, carried out in the Distributed Electrical Systems Laboratory (DESL) and the Power Electronics Laboratory (PEL) (Figure 17).

Key facts

The EPFL Demo site is the fusion of the two lab infrastructures, the DESL AC microgrid and an DC microgrid in the PEL. The 0.4 kV_{AC} microgrid is connected to the 20 kV MV network at node B01 via a step-down transformer. Thanks to combined infrastructure of the PEL and the DESL, an ACDC microgrid is developed, with most of the elements limited to below 50kW with their ratings. AC microgrid is based on the Council on Large Electric Systems (CIGRE) benchmark network, extended with creation of four DC links through bidirectional AC-DC converters. As the AC microgrid part is fully equipped, majority of new equipment is expected to be deployed on the DC side, on one of the newly created DC lines (Figure 18).

Figure 17: Illustration of the laboratory environment of the PEL and DESL, relevant for the HYPERRIDE project.

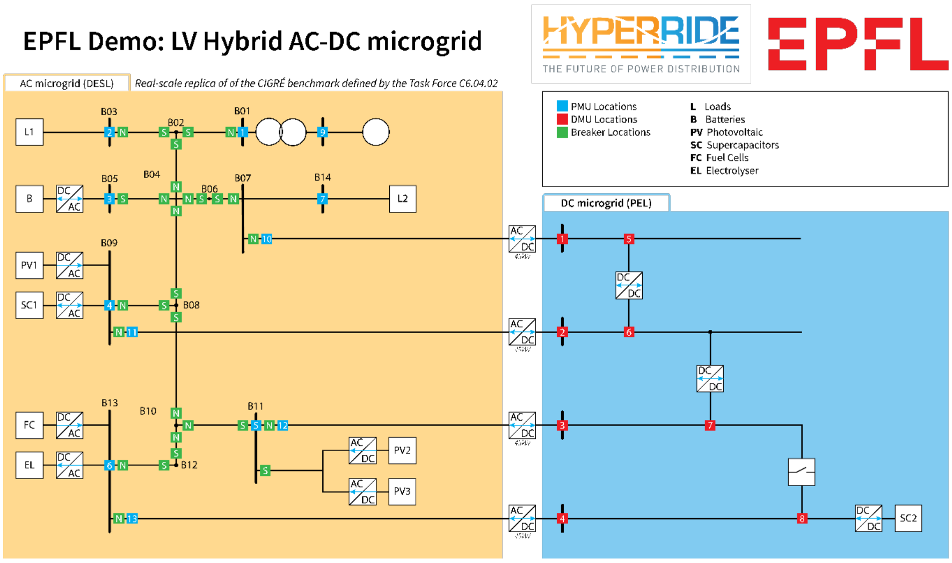


Figure 18: EPFL Demo: Layout of LV Hybrid AC-DC microgrid. Please note that system may evolve over the course of the project.

Infrastructure facts

Both AC and DC microgrid layouts are fully reconfigurable thanks to electromechanical controls of each line. Table 1, Table 2, Table 3 and Table 4 provide brief description of various pieces of equipment, majority of which is custom made and fully controllable by the user.

Table 1: EPFL DC microgrid equipment.

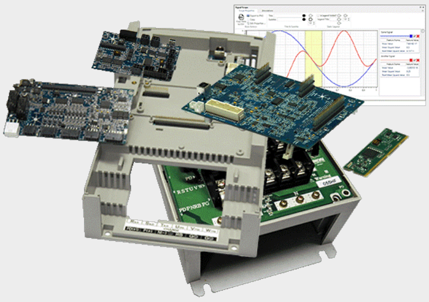
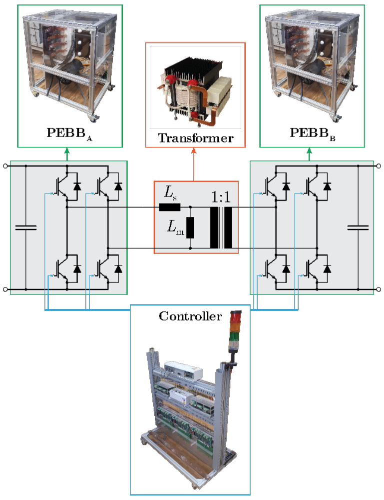
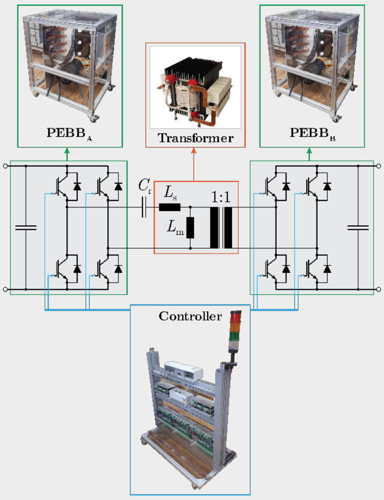
4 x AC-DC Converters: Power: 45kW (Hyundai N700-450HF) AC voltage : 400V DC voltage :750V Grid side filter: LCL Controller: LARA 100 custom boards by PERUN, allowing for full control in deployment of control SW on a TI DSP.	
1 x DC/DC Converter 1: DAB Converter Power : 100kW (max) DC voltage : 750V (on both sides) PEBB: 800V, 200Arms (1.2 kV Infineon IGBTs, Capacitor bank of 3mF) Transformer: 100kW, 10kHz Controller: ABB AC 800PEC allowing for full control development.	
1 DC/DC Converter 2: LLC Converter Power : 100kW (max) DC voltage : 750V (on both sides) PEBB: 800V, 200Arms (1.2 kV Infineon IGBTs, Capacitor bank of 3mF) Transformer: 100kW, 10kHz Controller: ABB AC 800PEC allowing for full control development. Please note that second DC-DC converter is developed with slightly different equipment available in the lab, but using identical principles and controller.	

Table 2: *EPFL DC microgrid equipment (continued).*

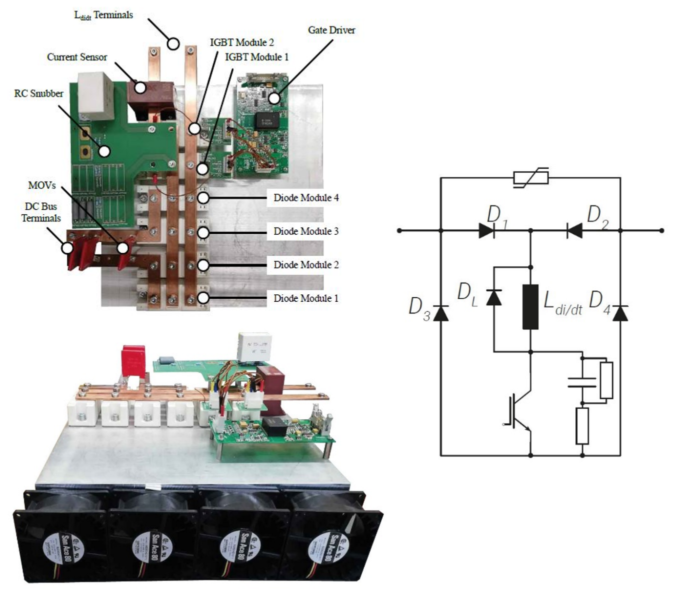
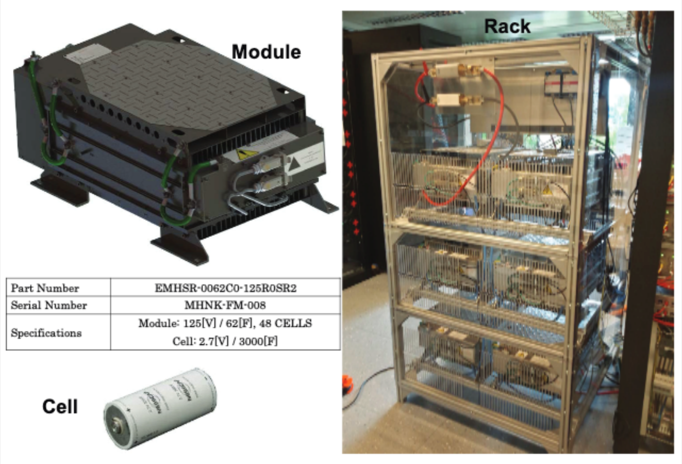
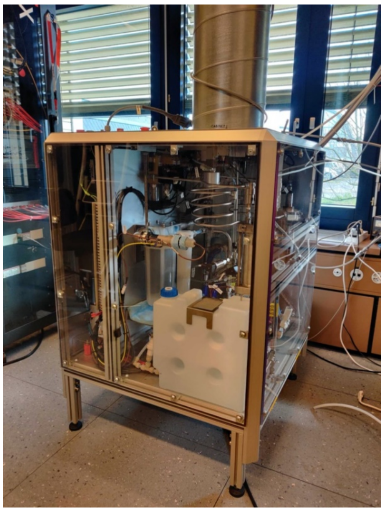
Solid-State Bus Tie Switch Ratings: 600V,200A Interruption time: 10µs Sub-devices: • MOV: LITTLEFUSE V421HG34 1100V,200A • Ldidt=50µF • RC snubber: 1µF+1.8 Ohm • Semiconductors: 1.2 kV devices • Diode: SEMIKRON SKKD150F12 • IGBT: SEMIKRON SKM150GAL12V Controller : RT-Box by PLEXIM Please note that this is custom made device (prototype) which is extensively tested already and available in quantity of 2.	
Supercapacitor bank Voltage : 600V Ratings: 2x2F (160kJ) Please note that DC-DC converter is not shown in the image.	
Leclanché StoraXe Storage Rack System SRS0029 Power/Energy : 25 kW – 25kWh Technology: Lithium-titanate technology Converter: IMPERIX custom made DC-AC converter	

Table 3: EPFL DC microgrid equipment (continued).

<table>
<tr>
<td>Supercapacitor bank
Power/Energy : 50kW – 0.8kWh
Manufacturer: 6 NESSCAP 125V 62F SR2 modules
Converter: IMPERIX custom made DC-AC converter</td>
<td>

<table>
<tr><td>Part Number</td><td>EMHSR-0062C0-125R0SR2</td></tr>
<tr><td>Serial Number</td><td>MHNK-FM-008</td></tr>
<tr><td>Specifications</td><td>Module: 125[V] / 62[F], 48 CELLS
Cell: 2.7[V] / 3000[F]</td></tr>
</table></td>
</tr>
<tr>
<td>Electrolyzer
Power : 5 kW
Technology : Proton-exchange-membrane
Storage : 0.9 MWh @200bar</td>
<td></td>
</tr>
<tr>
<td>Fuel Cell
Power : 15 kW (electrical)
Technology : Proton-exchange-membrane</td>
<td></td>
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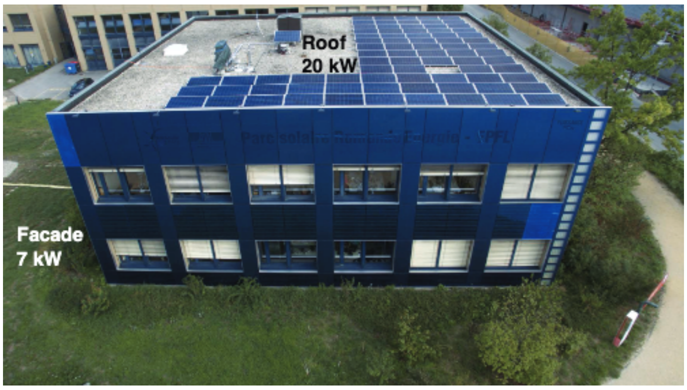
</table>

Table 4: *EPFL DC microgrid equipment (continued).*

Load Emulators Converters : 3xZENONE, fast dynamic AC converters – single phase Power : 30 kVA overall power (10 kVA per phase)	
PV Plants Facade : Fronius – 7 kW (commercial converter) Roof : Solarmax – 16 kW (commercial converter) Roof : Perun – 13 kW (custom made converter)	
Electric vehicle charging-station Power : 2x 22kW (Chademo 10kW)	

2.4.3 Terni (Italy)

Geographical location

ASM Terni S.p.A. is located in Terni and it is a multiutility fully owned by the local municipality. Terni is in Umbria region, named the green heart of Italy, 100km far from Rome (less than 1 hr by train - see Figure 19). Its population is 112.000 inhabitants; it is an industrial town with one of the oldest steelworks and one of the first hydro power plant in Italy. For this reason it is nicknamed the “steel City”. Today, Terni is a city completely renovated and human scale. To the vast industrial areas, in fact, alternate green landscapes (especially nearby the waterfall of Marmore), evidence of Roman ruins, medieval and industrial archeology. Terni is also known as the "City of St. Valentine" as its patron saint, St. Valentine, was born and became bishop in 197 BC and the remains are kept in the church that takes his name.

Figure 19: Italian pilot location.

Area details

Currently, ASM TERNI owns and operates the local power distribution grid, covering a surface of 211 km^2 and delivering about 380 GWh to 65.000 customers annually. The Distribution Grid overall length is 650km MV power line and 1.400 km LV power line. A high level schema of the MV grid is provided by Figure 20, the network is connected to the Transmission System Operator (TSO) by means of 3 primary substations and more than 650 secondary substation are also connected for providing energy to energy customers; it is worth highlighting that the topology is widely meshed and there are often many alternative path that allows back-feeding.

Nowadays, the ASM electric grid is characterised by a large number of distributed renewable energy sources embedded in the medium and low voltage distribution networks: 41 and 1325

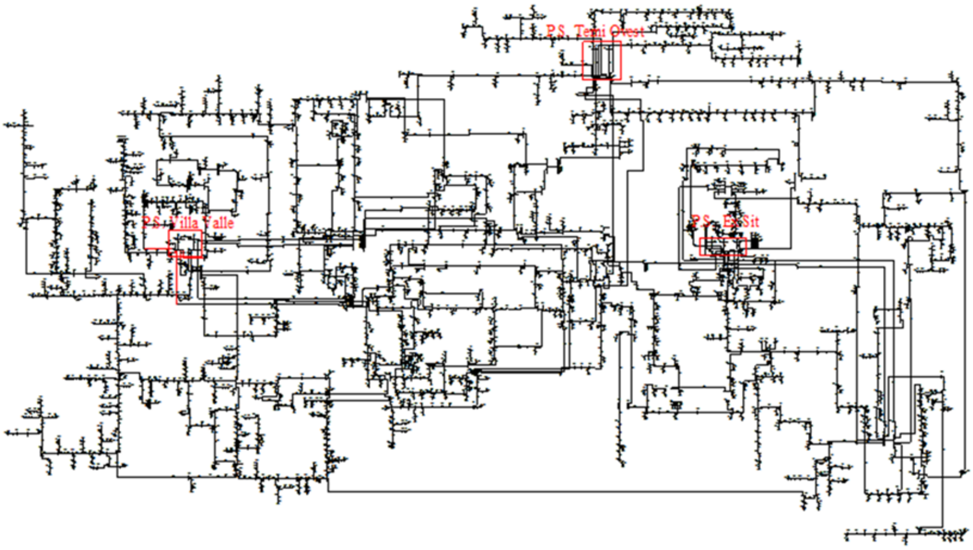


Figure 20: Distribution network owned and managed by ASM Terni.

units are currently connected respectively to the MV and LV networks. The LV power plants are mainly PV units, the increasing share of small producers is shown in Figure 21.

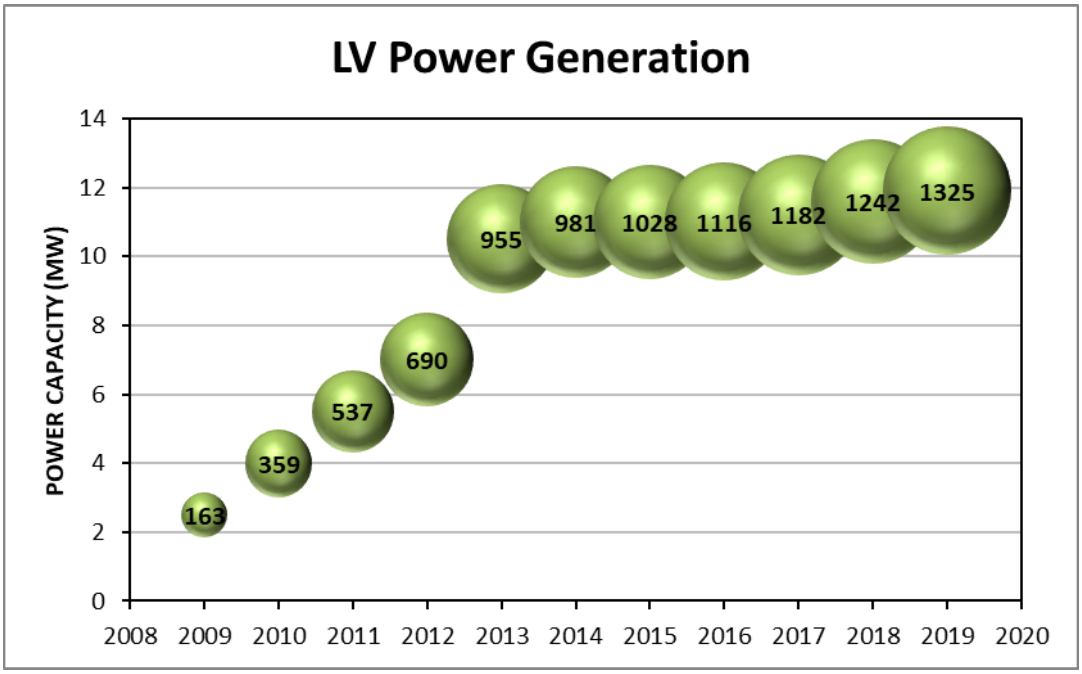


Figure 21: Producers connected every year to the LV distribution network.

With reference to the self produced energy in the Terni's distribution power grid, the mix of the yearly production is described in the Figure 22.

Moreover a state-of-the-art Supervisory Control and Data Acquisition (SCADA) system is currently used in remote control of the MV grid. The capillary penetration of the RES transformed the MV/LV distribution grid from a purely passive network – which, being operated in radial direction, characterised by mono-directional power flows (i.e. from the High-Voltage (HV) grid to

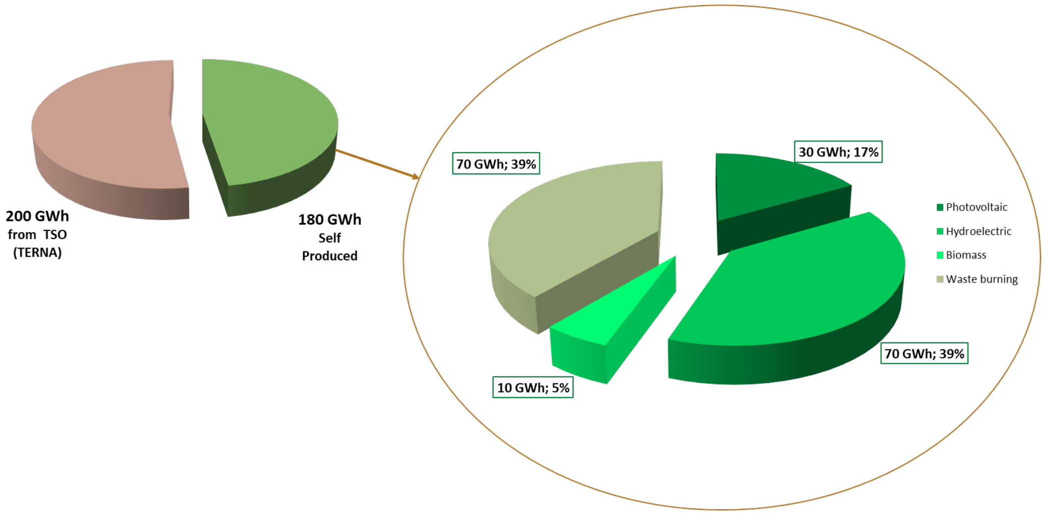


Figure 22: Energy mix of ASM distribution network in 2019.

final users) – into an active grid with significant bidirectional flows (i.e. from active users to the HV grid).

Key facts

In this context, HYPERRIDE project will leverage an existing urban district which corresponds to the ASM headquarters. It comprises some blocks of energy units connected to the Low Voltage (LV) network, notably:

- Two PV arrays (185 kWp and 60 kWp), that are able to produce about 230 MWh and 70 MWh every year, respectively.
- A Li-ion battery energy storage. A unit, able to be charged and discharged depending on the excess of local energy production.
- ASM Terni buildings which comprise:
  - a 4,050 m^2 three-storey office building;
  - a 2,790 m^2 single-storey building consisting of technical offices, a computer centre and an operation control centre;
  - a 1,350 m^2 warehouse.

  Usually the base load varies between 50 kW and 90 kW and peak load is between 120 kW and 170 kW, depending on seasonal factors.
- Three EV charging stations.

All the Italian Pilot units mentioned before are depicted in Figure 23.

Infrastructure facts

According to Figure 24, two secondary substations are involved in the trial: both are connected to the same Medium Voltage feeder and they are named ASM and SCOV; the former connects the building and the smaller PV plant (Figure 25) while the latter connects the bigger PV plant and one EV charging station (Figure 26). It is worth mentioning that some LV users (about 15) are also connected to SCOV substation whilst ASM substation basically hosts only ASM headquarters.

Figure 23: Overview of the Italian pilot site.

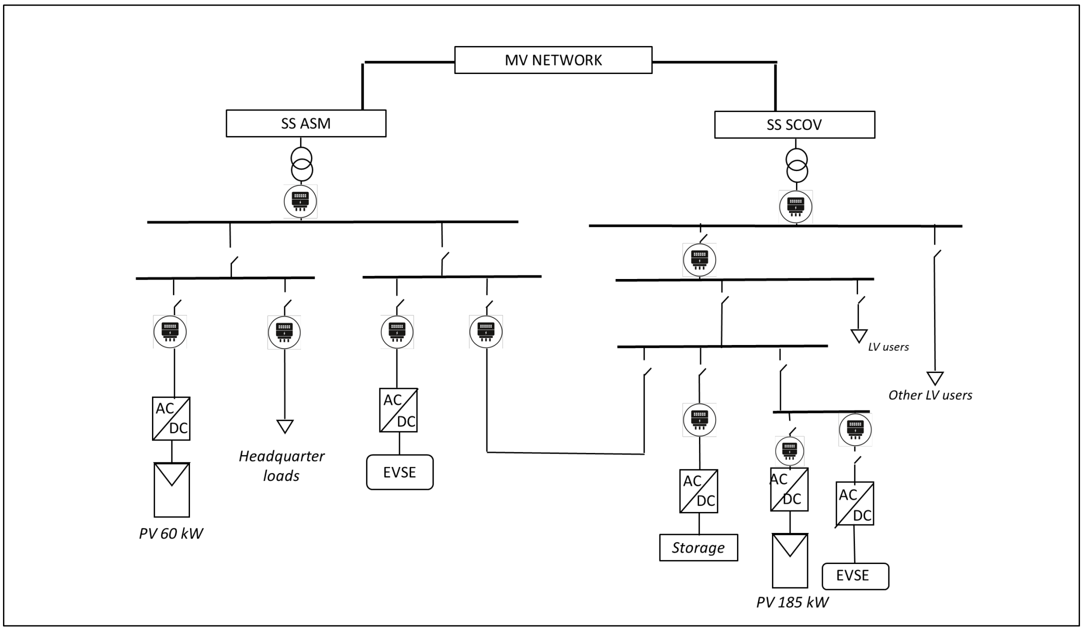


Figure 24: High level network schema of Italian pilot site.

Figure 25: 60 kWp PV power plant at the Italian pilot site.

Figure 26: 185 kWp PV power plant at the Italian pilot site.

3 Identified Key Performance Indicators

3.1 General

Key Performance Indicators (KPI)s are widely used as a tool for performance measurement. The general purpose is the generation of accepted parameters which can be used to:

- measure the absolute capability (KPI fulfilment) of a solution in absolute values
- measure the effectiveness of a new solution when compared to a previous one. DC solutions should improve the current situation using AC in relevant KPIs;
- compare solutions of the similar kind in terms of unified monitoring;
- provide insights in target fulfilment during operation.

The DC and hybrid ACDC installations in the project HYPERRIDE need to be assessed for all above mentioned points. The solutions need to be comparable with generally used AC installations. Therefore, the proposed KPIs lever on accepted KPIs from AC grid with added parameters, which are applicable only for DC. Further, the differences between the three demonstration sites within the project and existing solutions outside are large enough to make the direct comparison very complicated. Here, KPIs also serve as a tool to provide insight in common achievements and potential differences. With the EU climate targets as a general goal and derived targets for smaller systems the below defined KPIs also serve as a tool to assess the suitability of the solution with respect to target fulfilment; e.g. the share of renewable energy sources in the system can be directly derived from high level targets. Consequently, the KPIs are linked to indicative values if applicable.

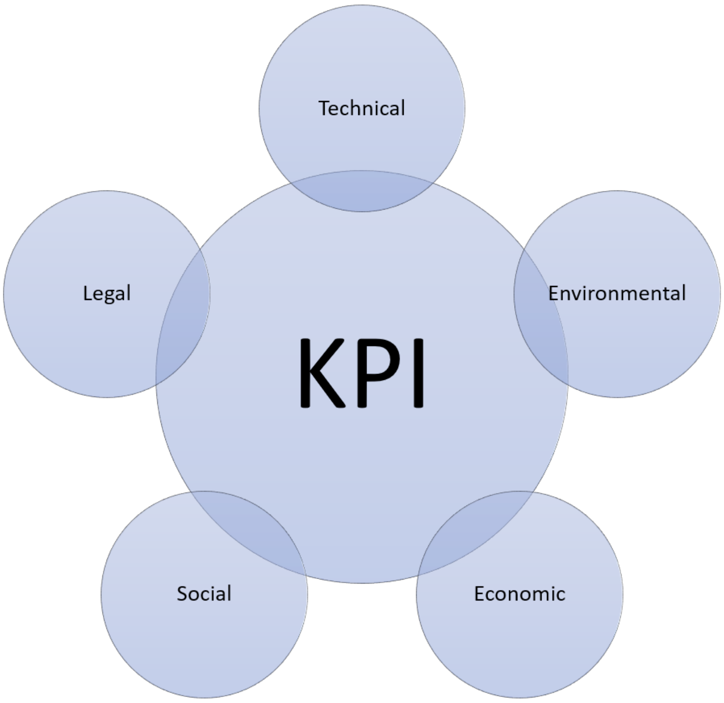


Figure 27: Domains of KPI definition

doi:10.5281/zenodo.4772144

3.2 Methodology

In previous work a general KPI clustering has been established with respect to the domain of perspective (see Figure 27). Due to the demonstration character of the project HYPERRIDE a main emphasis was put on technical and environmental indicators.

As a starting point, KPIs lever on previous work from various preceding projects in the area of electricity grids and smart cities. The novelty of the grid infrastructure is seen in the DC configuration which should co-exist with established AC installations. Consequently, it is seen as important to provide a certain interoperability between existing indicators and those which need to be developed to provide suitable tools for assessment. The projects that constituted the main sources, serving as a starting point for further refinement towards DC infrastructures, are listed in Table 5 below:

Table 5: Relevant projects for KPI definition.

Project name	Long name
DISCERN	Distributed Intelligence for Cost-Effective and Reliable Distribution Network Operation
DREAM	Distributed renewable resources exploitation in electric grids through advanced hierarchical management
EPIC-HUB	Energy positive neighborhoods infrastructure middleware based on energy—hub concept
GRID+	Supporting the Development of the European Electricity Grids Initiative (EEGI)
GRID4EU	Large-Scale Demonstration of Advanced Smart GRID Solutions with wide Replication and Scalability Potential for EUROPE
IDE4L	Ideal Grid for All
inteGRIDy	Integrated Smart GRID Cross-Functional Solutions for Optimized Synergetic Energy Distribution, Utilization Storage Technologies
IRIS	Integrated and Replicable Solutions for Co-Creation in Sustainable Cities
PlanGridEV	Distribution grid planning and operational principles for EV mass roll-out while enabling DER integration
SMILE	Smart Islands Energy System
STORY	Added value of STORage in distribution sYstems
SUCCESS	Securing Critical Energy Infrastructures SUCCESS - Securing Critical Energy Infrastructures
UPGRID	Real proven solutions to enable active demand and distributed generation flexible integration, through a fully controllable LOW Voltage and medium voltage distribution grid
WiseGRID	Wide scale demonstration of Integrated Solutions and business models for European smartGRID

The focus of the work was to identify gaps between existing KPIs for other use cases and to consequently bridge open areas for new installations (see Figure 28).

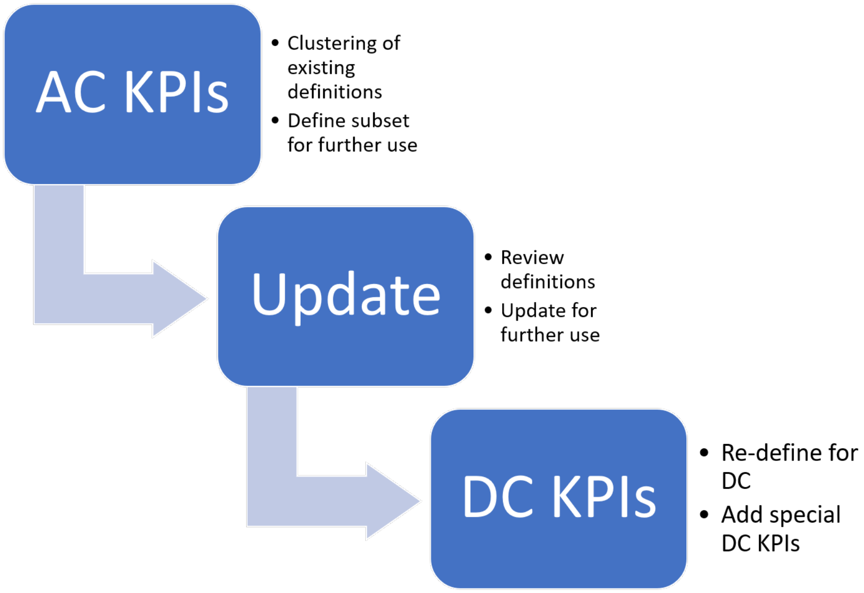


Figure 28: Procedure of KPI development.

3.2.1 Stakeholders

The stakeholder involvement presented here follows widely (Pramangioulis et al., 2019) (see Figure 29).

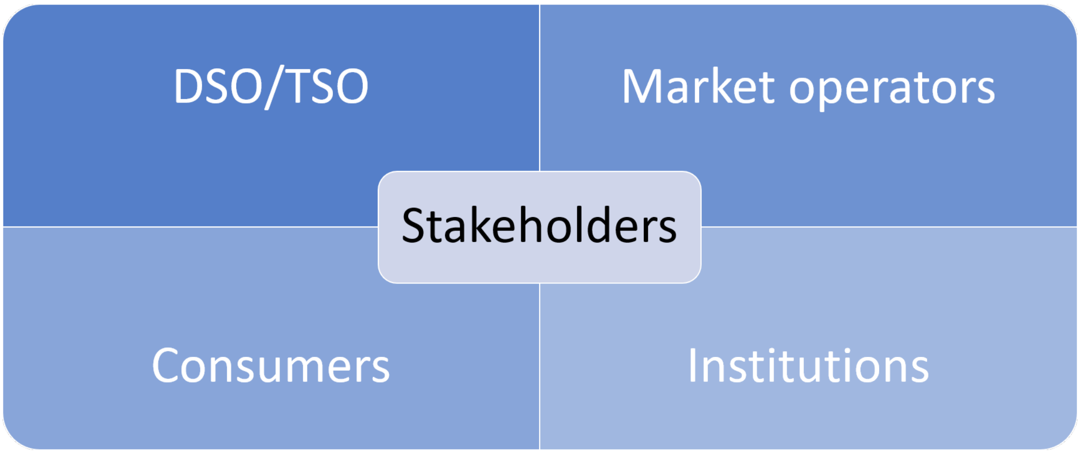


Figure 29: Stakeholders for DC grids.

Institutions

Institutions are defined as all entities which are not directly involved in the infrastructure planning and operations, but merely provide the framework for establishment of such a system. This involves e.g.:

- International authorities;
- National authorities;
- Regulators;
- Standardization commitees.

DSO/TSO

In the project HYPERRIDE the main emphasis for this stakeholder group is put on DSOs as the systems are focusing on low and medium voltage. The main responsibilities of the DSO are to provide (*Mapping of TSOs' and DSOs' Roles and Responsibilities Related to Market Design to Enable Energy Services*, 2015):

- Energy services: to deliver energy to the customer;
- Energy efficiency improvement: to increase the efficiency by means of technological, behavioural and/or economic changes;
- Energy efficiency/demand side management: to influence with an holistic approach timing and amount of energy consumption;
- Metering services: to carry out measurements based on Smart Metering infrastructure;
- Ancillary services: to deploy services such as power quality improvement in order to operate the system safely.

Market Operators

Market operators are grid market participants aside from DSO/TSO scheme. This involves generation (DER/RES) operators, storage owners and potential auxiliary service providers up to vehicle-to-grid services and power quality units. Also future energy communities fall into this category.

Consumer

The role of the consumer (residential, industrial) will become more important in the near future with increasing participation in the grid operation by generation and variable loads as well as possible participation in market activities as prosumers. Hence, the change from passive to active role consequently leads to a higher interest in the performance of the grid. The following aspects remain of basic interest:

- Low energy prices;
- Secure and reliable energy supply.

However, with the digitisation of the electricity grid new interests will see increasing importance:

- Interaction with grid to engage market participation;
- Cost reduction by increasing self-consumption.

Besides the interest in the KPIs in general (e.g. technical), consumers also become the source of KPIs. Especially for social KPIs the impact on the consumer in terms of noise, landscape, green energy etc. is discussed. This is mainly done via questionnaires and a proposed tool is the use of Likert scale.

3.3 Technical KPIs

Technical KPIs are evaluated to provide insight in technical setup and functionality. The values are based on physical measurement (e.g. voltages and currents) gathered in the network at every level.

3.3.1 Share of RES

The integration of Renewable Energy Sources (RES) is an important factor of future electric energy systems. Hence, the share of locally produced energy from RES with respect to the overall energy consumption over a period of time, such as a year, can also be applied for ACDC hybrid installations. Definitions can be found in e.g. (Angelakoglou et al., 2019):

$$Share\_of\_RES = E_{RES}/E_{tot} \tag{1}$$

where E_{RES} is the locally produced energy and E_{tot} the total consumption. It is important to highlight that RES also includes bulk generation which is not a focus point in the HYPERRIDE project.

Table 6: KPI for Share of RES.

Name of KPI	Share of RES
Description	RES penetration for covering electrical needs
Unit	percent
Stakeholders in Charge	Institutions, DSO/TSO

3.3.2 Share of DER

The share of DER is tightly linked to the share of RES in future electricity grid and based on the increasing deployment of renewables and interest in local energy communities. It can be therefore be assumed that the KPI values approach equality in the future. However, DER also involves non-renewables such as local and decentralised generation from fossils for various reasons.

$$Share\_of\_DER = E_{DER}/E_{tot} \tag{2}$$

where E_{DER} is the produced energy from Decentralized Energy Resources (DER) and E_{tot} the total consumption.

Table 7: KPI for Share of DER.

Name of KPI	Share of DER
Description	Share of DER in the energy mix
Unit	percent
Stakeholders in Charge	Institutions, DSO/TSO

3.3.3 Share of EVs

Within literature this KPI is often part of social KPIs in terms of "EV acceptance" (e.g.(Pramangioulis et al., 2019) . However, with reasonable shares of EVs in any area this factor became already a technically relevant one. The respective social KPI has been removed.

Table 8: *KPI for Share of EVs.*

Name of KPI	Share of EVs
Description	Share of EVs wrt. total amount of vehicles
Unit	percent
Stakeholders in Charge	Institutions, DSO/TSO, consumers

3.3.4 Peak Shaving

KPIs related to peak power have been discussed in literature (e.g. (Gubina et al., 2018)). Peak shaving by using energy storages (e.g. batteries) reduces fluctuations in energy demand and avoids therefore oversizing of components and reduces power-based grid tariffs. In principle the assessment compares the case without any measures of peak reduction with the case of measures in place and can be calculated as

$$\frac{P_{RED} - P_{BASE}}{P_{BASE}} \cdot 100 \tag{3}$$

where P_{RED} is the reduced (average) peak power and P_{BASE} the base scenario (average) peak power.

Table 9: KPI for Peak Shaving.

Name of KPI	Peak shaving from the side of consumption
Description	Reduction of power peaks
Unit	percent of power peak reduction
Stakeholders in Charge	DSO/TSO, consumer, market operators

3.3.5 Forecasting

With an increasing share of renewable production (e.g. wind and PV) it became also increasingly important to have a reliable forecast on the expected generation with respect to the near (minutes to hours) and mid-term future (day-ahead). As there might be an impact on grid stability when the forecast is not met, it is possible that the system operator imposes potential penalties for contract violations on the operator of the power plant, consequently decreasing revenues. Hence, it is of vital importance for all parties that the offset of generation with respect to forecast is as small as possible. The proposed KPI uses the root mean square error of a time series. For comparison with other assets or grids it would be more recommendable to derive a normalised error.

In literature (e.g. (Oprea & Bâra, 2017)), a similar KPI, is also defined as Performance Index (PI):

$$PI = \frac{E_{prod}}{E_f} \tag{4}$$

where E_{prod} is the produced energy while E_f is the forecast energy for the respective time.

Further, it can be distinguished between the energy (kWh; *EPI* - energy performance index) as basis and (effective) power (kW; *PPI* - power performance index). This ratio approaches unity in case of optimal forecasting but can also be larger than 1. For further analysis of a time series an error based approach is nevertheless advisable.

Table 10: KPI for Forecasting.

Name of KPI	Generation Forecasting Accuracy
Description	Confidence or fuzziness (risk) in RES generation forecasting
Unit	(normalized) RMSE (root mean square error)
Stakeholders in Charge	DSO/TSO, market operators, involvement of consumers possible (e.g. PV data)

3.3.6 Energy Losses

KPIs for energy losses on system level can either be calculated as an absolute value (kWh/year), as an efficiency value based on the yearly energy consumption in the grid or as an improvement value when compared to a business as usual scenario (here potentially an AC grid). In accordance with (Development, 2012) the KPI can be calculated via

$$Energy\_Losses\_KPI = \frac{E_{loss,BaU} - E_{loss,DC}}{E_{tot}} \cdot 100 \tag{5}$$

where $E_{loss,BaU}$ represents the losses in an business as usual scenario (AC), $E_{loss,DC}$ the grid losses in the respective DC installation and E_{tot} the yearly consumption in the assessed grid section.

Table 11: KPI for Energy Losses.

Name of KPI	Energy Losses
Description	Yearly amount of energy lost on grid's conductors, transformers, etc.
Unit	kWh/yr (or (kWh/yr)/(kWh of grid/yr) in percent
Stakeholders in Charge	DSO/TSO, market operators

3.3.7 Voltage Variations

There are two considerations to be taken for this KPI. The first one is the deviation of the yearly average voltage (15 min samples) at a certain node from the specified value. The second is the number of specification violations taking place throughout the year.

Table 12: KPI for Voltage Variations.

Name of KPI	Voltage variations
Description	Difference between the actual voltage supplied to MV/LV users and the nominal value
Unit	percent
Stakeholders in Charge	DSO/TSO, consumers, institutions

Table 13: *KPI for Amount of Voltage Variations.*

Name of KPI	Amount of voltage variations
Description	Number of times the grid section violated the voltage specification limits per year
Unit	unity
Stakeholders in Charge	DSO/TSO, consumers, institutions

3.3.8 Energy Ratio

The KPI provides insight in the supply of an area with local renewable resources and puts them in relation to the overall energy demand. The value can also exceed the local demand, indicating a surplus of energy. This is an average throughout the year. A timely comparison follows with the subsequent KPI.

Table 14: KPI for Energy Ratio.

Name of KPI	On-site energy ratio
Description	Relation between the annual energy supply from local renewable sources and the annual energy demand
Unit	percent
Stakeholders in Charge	DSO/TSO, institutions

3.3.9 Surplus-Deficit

This KPI relates to the energy ratio but describes a surplus or a deficit on a timely basis (here: hourly). Basically this KPI can consist of two values which provide an indication of renewable potential.

Table 15: KPI for Surplus and Deficit.

Name of KPI	Maximum Hourly Surplus Deficit (MHS-Dx)
Description	The maximum value of how much bigger or smaller the hourly local renewable supply is than the demand during the hour (per year)
Unit	kWh
Stakeholders in Charge	DSO/TSO, institutions, consumers/prosumers

3.3.10 Energy Curtailment

An initial assessment of grid curtailment may be quantified as the energy NOT withdrawn from renewable sources due to lack of consumption ((Yang, Jurasz, Hailong Li and, & Yan, 2019)).

$$Energy\_Curtailment\_KPI = \frac{E_{RESloss,curtailment}}{E_{tot,RES} + E_{RESloss,curtailment}} \cdot 100 \tag{6}$$

where $E_{RESloss,curtailment}$ is the RES energy lost due to curtailment and $E_{tot,RES}$ is the total energy supplied.

Table 16: *KPI for Energy Curtailment.*

Name of KPI	Reduced Energy Curtailment of RES/DES
Description	The difference between the energy curtailments before and after the integration of a/all the proposed solutions
Unit	percent
Stakeholders in Charge	DSO/TSO, market operators, consumers/prosumers

3.3.11 Grid Congestion

A initial assessment of grid congestion may be energy NOT withdrawn from renewable sources due to grid limitations ((Yang et al., 2019)).

$$Grid\_Congestion\_KPI = \frac{E_{RESloss,congestion}}{E_{tot,RES} + E_{RESloss,congestion}} \cdot 100 \tag{7}$$

where $E_{RESloss,congestion}$ is the RES energy lost due to congestion and $E_{tot,RES}$ is the total energy supplied.

Table 17: *KPI for Congestions.*

Name of KPI	Grid Congestion
Description	Grid sustainability to peaks
Unit	percent
Stakeholders in Charge	DSO/TSO, consumers/prosumers

3.3.12 (Battery) Storage Degradation

The (battery) storage performance is often assessed via variations and evaluation of round trip efficiency tests ((Blair et al., 2021)). These parameters are temperature and power dependent and therefore require careful test execution. Typical values of degradation are up to 3% capacity loss per year ((Smith et al., 2017). Although originally defined for battery storage the KPI itself is applicable for all storage technologies such as flywheel, supercapacitors etc.

Table 18: *KPI for Storage Degradation.*

Name of KPI	(Battery) Degradation Rate
Description	The yearly storage capacity loss from (battery) storage due to degradation
Unit	percent
Stakeholders in Charge	DSO/TSO, marktet operators, consumers

3.3.13 Interruption Frequency

System Average Interruption Frequency Index (SAIFI) is a common parameter for power supply reliability and already established for AC grids. In general this value is calculated on yearly basis and divided into several subcategories:

- With respect to voltage level of the origin of the failure;
- Exceptional events;
- Planned (means that the network user was given prior notice about the interruption);
- Unplanned;
- Cumulative.

Table 19: KPI for Interruption Frequency.

Name of KPI	System Average Interruption Frequency Index (SAIFI)
Description	Measures the average frequency of power-supply interruptions in the system (indicatively would better be <1.5 interruptions per customer and year)
Unit	interruptions/(customer x year)
Stakeholders in Charge	DSO/TSO, consumers

3.3.14 Interruption Duration

System Average Interruption Duration Index (SAIDI) is a common parameter for power supply reliability and already established for AC grids. In general this value is calculated on yearly basis and divided into several subcategories:

- With respect to voltage level of the origin of the failure;
- Exceptional events;
- Planned (means that the network user was given prior notice about the interruption);
- Unplanned;
- Cumulative.

Table 20: KPI for Interruption Duration.

Name of KPI	System Average Interruption Duration Index (SAIDI)
Description	Measures the average cumulative duration of power-supply interruptions in the system (indicatively would better be <150 min per customer and year)
Unit	minutes/(customer x year)
Stakeholders in Charge	DSO/TSO, consumers/prosumers

3.3.15 Unbalance

Unbalance of line voltages is a common parameter for 3-phase AC lines. For the case of DC installations the parameter is only applicable for 3 wire configurations as seen e.g. with ± 350

V plus 0 V. As the project also includes hybrid ACDC installations it is worth mentioning that the calculation of AC unbalance remains valid. Here, e.g. (Gopalan, Vasudevan, Kumar, & Shanmugam, 2018) clusters possible calculation in three groups:

- Definitions using approximate formulas to simplify the calculations without phasor estimation such as IEEE 1159;
- Based on sequence calculations but still approximate such as most IEC standards;
- Calculation of unbalance referring to the average source voltages such as NEMA MG 1.

Table 21: KPI for AC Unbalances.

Name of KPI	Unbalance of 3-phase AC voltages
Description	Difference in the voltage of the three phases
Unit	percent
Stakeholders in Charge	DSO/TSO, consumers/prosumers

A proposed unbalance KPI for DC grids would potentially involve a pure symmetry calculation regardless of the nominal values. Deviations with respect to nominal values are covered via voltage variations.

Table 22: KPI for DC Unbalances.

Name of KPI	Unbalance of 3-wire DC-lines
Description	Difference in the voltage (pos and neg) of 3 wire DC installations
Unit	percent
Stakeholders in Charge	DSO/TSO, consumers

Further analyses and recommendations can be taken from IEC TR 63282:2020 Part 6.10.

3.3.16 Distortion

At a first glance, harmonic distortion does not apply for DC grids as there is no base frequency triggering harmonics. While this is generally true for pure DC grids, not including potential resonance or beat effects, this not necessarily true for hybrid ACDC grids. It is known, that a driving n-th harmonic on the AC side can trigger n-1 or n+1 harmonic on the DC side as well. A harmonic imposed this way can further propagate to other AC connections via the DC side. Though a such injected harmonic on the AC side does not again back trigger further harmonics towards DC this is not true for DC harmonics which can inject further harmonics back to the AC side. Therefore, it is also beneficial to monitor any harmonic of the AC base frequency also on the DC installation to avoid any kind of stability problems which might be caused by unstable system setups.

Harmonic distortion in the frequency band depends on the switching frequency of converters and power topologies. A comparison of average DC and AC Root Mean Square (RMS) values might be the basis for setting power quality indices for LVDC systems. (IEC TR 63282:2020 Part 6.4).

Table 23: *KPI for AC Distortions.*

Name of KPI	Harmonic distortion for ACDC hybrid grids
Description	The Total Harmonic Distortion unit (THDu) indicates the distortion of the voltage wave. There are other Total Harmonic Distortion (THD) factors that give relative information about the power, the current etc. (indicatively would be better < 5%
Unit	percent
Stakeholders in Charge	DSO/TSO, consumers/prosumers

Table 24: *KPI for DC Distortion.*

Name of KPI	DC variant of THD
Description	The root mean square voltage of all the AC components in the DC ripple in relation to the average DC-Voltage
Unit	percent
Stakeholders in Charge	DSO/TSO, consumers/prosumers

3.3.17 Storage Losses

Storage energy losses are linked to the ratio of energy stored and energy regained from the storage, defined as round trip efficiency. While the round trip efficiency is measured with full cycles and can be estimated for technologies like batteries (75% to 90%) or flywheels (80% to 90%), storage losses are further affected by the storage management as well.

Table 25: *KPI for Storage Losses.*

Name of KPI	Storage energy losses
Description	Losses because of energy storage solutions
Unit	percent
Stakeholders in Charge	DSO/TSO, market operators, consumers

3.3.18 Self Supply

For this KPI it is important to properly define the system boundaries. Within HYPERRIDE the boundaries are given by the nature of the demonstration and can vary from LVDC/MVAC interface to MVDC/MVAC or even LVDC/LVAC.

Table 26: *KPI for Self Supply.*

Name of KPI	Degree of self-supply
Description	Measures the percentage of PV generation which is used for self-supply, and not injected to the grid
Unit	percent
Stakeholders in Charge	DSO/TSO, market operators

3.3.19 Frequency Control (Hybrid ACDC)

Frequency control is only relevant for AC part of hybrid installations and calculated based on state-of-the-art procedures. Here, the continuous service band is given by 50 Hz ± 0.02 Hz.

Table 27: KPI for AC Frequency Control.

Name of KPI	Frequency Control
Description	Calculates the percentage of times that the average value of the fundamental frequency measured over periods of 10 s goes out of the stated ranges
Unit	percent
Stakeholders in Charge	DSO/TSO, consumers

3.3.20 ICT and Cyber Security

Although there is a wide range of KPIs defined with respect to cyber security and ICT solutions, the most relevant from grid perspective are directly linked to the availability of the infrastructure. Hence, the proposed KPIs focus on the impact of ICT related failures on the provision of energy to the customers.

Table 28: KPI for ICT Confidentiality.

Name of KPI	Confidentiality factor
Description	Number of Messages that reached the intended recipient / Number of Messages that reach the unintended recipient “A loss of confidentiality is the unauthorized disclosure of information”
Unit	percent
Stakeholders in Charge	DSO/TSO, consumers, market operators

Table 29: KPI for ICT Integrity.

Name of KPI	Integrity factor
Description	Number of Messages that could not be modified/viewed by un-authorized recipients / Number of Messages that could be modified/viewed by un-authorized recipients “A loss of integrity is the unauthorized modification or destruction of information.”
Unit	percent
Stakeholders in Charge	DSO/TSO, consumers, market operators

3.3.21 Cumulative Hybrid KPIs

In general, for hybrid ACDC grids some of the KPIs discussed above involve separate calculations for AC and DC side. In case one single KPI was needed it would be proposed to calculate it via a weighted factor. The basis for the weights needs to be discussed as not all grid values serve as a proper tool. For example net energy might approach to 0 in case of high share of self consumption. For large amounts of energy exchange between the grids some share might be counted twice. If one uses the load as a weighting parameter it would trigger the question if the other grid is also counted as a load in case of energy exchange or if this amount is subtracted. A first approach could be to use average power consumption or peak power consumption as initial weighting parameters.

3.4 Environmental KPIs

These KPIs focus on the efficiency of an application in terms of environmental impact. While some are part of an assessment during operation, some are based on information to be acquired even during production of the needed components. On value known as Energy Return On (Energy) Invested (EROI) describes the amount of energy gained from a resource with respect to energy needed to access the resource. Another group depends on comparison with another kind of solution in order to assess the improvement potential.

3.4.1 Energy Return

The ratio of energy return to energy invested is an important number for any renewable setup to assess the impact of the proposed solution. As clear as the definition is, the estimation of the related values, especially for the energy invested, is not calculated easily and published estimated show a certain deviations for PV installations (e.g. (Ferroni & Hopkirk, 2016)). (Raugei et al., 2017) analysed the EROI for PV installations and addressed further implications.

A general matrix based bottom up approach was presented by Brandt *et al.* (Brandt, Dale, & Barnhart, 2013) enabling analysis from well to application. A special use case described there is PV module manufacturing and installation. An outlook for the development of EROI values for various technologies towards 2050 can be found with (Fabre, 2019).

Table 30: KPI for Energy Return.

Name of KPI	Energy Return on (Energy) Invested (EROI)
Description	EROI taking into consideration the component's whole life time
Unit	MWh (usable energy)/MWh (energy used to obtain that energy resource)
Stakeholders in Charge	DSO/TSO, consumers

3.4.2 CO_2 impact

The direct CO_2 emissions need to be measured at generation sites or other assets emitting carbon dioxides. As a benchmark value the generation with gas has been proposed (*Environmental Key Performance Indicators - Reporting Guidelines for UK Business*, 2006). A more meaningful might be the comparison with the most recent electric energy generation mix which will see an increase of the renewable energy share for the near future and consequently will decrease the tons saved per annum from year to year. An additional improvement could be a normalised KPI based on the ratio of improved and conventional CO_2 emissions.

Table 31: KPI for CO_2 savings.

Name of KPI	CO_2 tonnes saved
Description	Tons saved per annum as compared with gas and grid electricity
Unit	tons CO_2
Stakeholders in Charge	DSO/TSO, consumers

3.4.3 Noise Pollution

Prolonged exposure to noise can negatively affect the health of nearby residents. Potential impacts are disturbed sleep, lower enjoyment of outdoor life, less ability to open windows when indoors. A KPI definition could be in accordance with ISO 1996-2:1987 "Acoustics — Description and measurement of environmental noise" with the ratio of people affected with noise exceeding 55 dB(A) to the total number of inhabitants.

To assess changes in noise pollution the above defined ratio could be compared to the condition before the installation. The best way of comparing the two is to subtract the old ratio from the new ratio. Positive values lead to a nominal worse condition while negative values lead to an improvement of the general noise pollution. However, the definition will not assess individual changes of and for affected inhabitants. Further, if the value of 55 dB(A) is exceeded it is not taken into account by how much it is violated.

Table 32: KPI for Noise Exposure.

Name of KPI	Noise pollution exposure
Description	Noise pollution in ratio of residential areas exceeding 55 dB(A) and total number of inhabitants
Unit	percent
Stakeholders in Charge	Institutions, market operators, consumers

Table 33: KPI for Noise Exposure Changes.

Name of KPI	Noise pollution exposure changes
Description	Noise pollution percentage after installation minus the condition before installation
Unit	unity
Stakeholders in Charge	Institutions, market operators, consumers

3.4.4 Fossil Fuel Reduction

The direct use of fossil fuel at generation sites is put into relation to a benchmark value based on fossil fuel production as been proposed (*Environmental Key Performance Indicators - Reporting Guidelines for UK Business*, 2006). A more meaningful definition might be the comparison with the most recent electric energy generation mix which will see an increase of the renewable energy share for the near future and consequently will decrease fuel saved per annum from year to year. An additional improvement could be a normalised KPI based on the ratio of improved and conventional fuel consumption.

Table 34: KPI for Fossil Fuel Reduction.

Name of KPI	Reduced fossil fuel consumption
Description	Reduction in the fossil fuels consumption for power generation
Unit	TOE/year
Stakeholders in Charge	Institutions, DSO/TSO

3.4.5 Sustainability and Efficient Use of Material Resources

Based on European Commissions 2030 Agenda sustainable goals were fixed to safeguard our planet, highlighted fundamental role of sustainability issues with environmental, social and economics dimensions (Sustainability 2019, 11, 5742; doi:10.3390/su11205742). Following environmental KPIs were identified in this paper (literature study): waste generated per thousand product units, greenhouse gases rate (refer to KPI CO_2 impact 3.4.2), hazardous material ratio, dangerous waste generated rate, energy intensity, electricity consumption, rate, soil use rate, water use rate, amount of environmental penalties, environmentally affecting gases, carbon footprint rate, Sulphur dioxides (SOx emissions), nitrogen oxides (NOx emissions), pollution indicators.

Table 35: KPI for Hazard Materials.

Name of KPI	Hazard material ratio
Description	Reduction heavy metals like copper, aluminium, mineral oil and magnetic plates for power transformers (recycled material used/tot material used)
Unit	percent
Stakeholders in Charge	Institutions, DSO/TSO

Table 36: KPI for Waste Reduction.

Name of KPI	Waste reduction rate
Description	Waste generated per thousand product units
Unit	kg/1000 product units
Stakeholders in Charge	Institutions, DSO/TSO

Table 37: KPI for Material Recycling.

Name of KPI	Percentage of reusable/recycled material
Description	Recycled material used/tot material used
Unit	percent
Stakeholders in Charge	Institutions, DSO/TSO

Table 38: KPI for Production Units.

Name of KPI	Energy used per thousand product units
Description	Total consumption of resources (in kWh) per thousand products (1/1000 product units)
Unit	kWh/1000 product units
Stakeholders in Charge	Institutions, DSO/TSO

3.5 Economic KPIs

In this section, the main economic and financial KPIs which are essential to evaluate the HYPERRIDE solutions from economic perspective, are defined and elaborated.

3.5.1 Net Present Value

Net Present Value (NPV) is an indicator to measure the profitability of an investment and compare its profitability with other investment options. NPV calculates the present value of upcoming cash flows that can be earned from an investment project during its lifetime (Jain, 1999). As shown in Equation 8, NPV is equal to discounted benefits minus discounted costs over a specific time span. In this equation, i is the time, T is the time span, r is discount rate, B_i is the benefits at time t and C_i is the costs at time t. A positive NPV means that the decision has added value for decision makers and negative NPV means that the investment decision will bring losses to the decision makers.

$$NPV = \sum_{i=0}^{T} \frac{B_i - C_i}{(1+r)^i} \tag{8}$$

In comparison to other economic KPIs, NPV is more appropriate for evaluating investment options that are expected to continue for a longer period. Besides, NPV is a better measure in case if reinvestments along the project lifespan happen. Additionally, in order to rank the profitability of different projects, NPV is a better measure and calculates additional surplus of each project.

Table 39: KPI for Net Percent Value.

Name of KPI	Net Present Value
Description	The present value of upcoming financial cash flows that can be earned from an investment during its lifetime. If NPV > 0, then the investment is profitable.
Unit	€
Stakeholders in Charge	Network operators (DSO/TSO), Electric utilities, Prosumers and Consumers, Industries

3.5.2 Internal Rate of Return

Internal Rate of Return (IRR) is another KPI to evaluate the profitability of investment decisions. IRR is a discount rate at which the net present value of all cash flows is equal to zero (Lin, 1976). IRR is appropriate for evaluating projects that are expected to continue for a shorter period. However IRR does not provide much information about profitability as NPV does. For instance, IRR does not provide the surplus of the investment and is not recommended to use for ranking the investment projects based on their profitability (it is possible that the project that has highest IRR, does not have the highest NPV). Besides, In case of reinvestment, IRR gives several values and it is not recommended for the projects which include reinvestments. The equation for IRR is given in equation 9.

$$\sum_{i=0}^{T} \frac{B_i - C_i}{(1 + IRR)^i} = 0 \tag{9}$$

Table 40: KPI for Internal Rate of Return.

Name of KPI	Internal Rate of Return
Description	IRR calculates the discount rate that lets the NPV of cash inflows from an investment project equal to 0. The project will be profitable, if the IRR of investment project is greater than cost of capital of the company.
Unit	-
Stakeholders in Charge	Network operators (DSO/TSO), Electric utilities, Prosumers and Consumers, Industries

3.5.3 Payback Period

The payback period is the time period which is required to recover the total investment cost of a project. This KPI is only defined for the investment projects that are able to recover their costs within their life time. The point at which the total investment cost are recovered is known as break-even point as well. The payback period is calculated by comparing cumulative benefits and cumulative costs along the project life time and, then, finding the time at which cumulative benefits become equal to cumulative cost.

Table 41: KPI for Payback Period.

Name of KPI	Payback Period
Description	The period of time needed for that the cumulative benefits from an investment becomes equal to the cumulative costs.
Unit	time (year,month)
Stakeholders in Charge	Network operators (DSO/TSO), Electric utilities, Prosumers and Consumers

3.5.4 Return on Investment

Return On Investment (ROI) is another important economic KPI for investment decision making. As defined in equation 10, ROI is a ratio between the net surplus and investment costs. ROI is mainly used to evaluate the efficiency of an investment or compare several investment options in a decision making process. An investment option with higher ROI is favourable compared to the other options.

$$ROI = \frac{total\ revenues - total\ costs}{total\ costs} \tag{10}$$

Table 42: KPI for Return of Investment.

Name of KPI	Return on Investment (ROI)
Description	ROI is a ratio between the net surplus and investment costs
Unit	percent
Stakeholders in Charge	Network operators (DSO/TSO), Electric utilities, Prosumers and Consumers

3.5.5 Annuity

Annuity is a series of periodic payments made at regular, fixed intervals whereas the length of this interval is called the annuity period. Annuity allows for the assessment of extension or replacement investments as well as the comparison of investments with different capital costs and useful life (Olfert & Reichel, 2012). Annuity a is level amortisation of a principal amount C_0 that includes interest r and is to be paid within a given period i:

$$a = C_0 * \frac{(1+r)^i * r}{(1+r)^i - 1} \tag{11}$$

Table 43: KPI for Annuity

Name of KPI	Annuity Gain
Description	Level amortisation including interest
Unit	€
Stakeholders in Charge	Network operators (DSO/TSO), Electric utilities, Prosumers and Consumers

3.5.6 Levelised Cost of Electricity

Levelised cost of electricity LCOE is the assessment of the total cost to build and operate a power-generation unit over its lifetime C_L divided by the doíscounted total output of the unit over lifetime E_L. LCOE can be used to compare different technologies with different project size, life time, capital cost, return, risk and capacity. LCOE represents the minimum cost that needs to be covered to achieve a break-even over the lifetime of the project (Lai & McCulloch, 2017).

$$LCOE = \frac{C_L}{E_L} \tag{12}$$

Table 44: *KPI for Levelised Cost of Electricity*

.

Name of KPI	LCOE
Description	Life cycle assessment of the total cost to build and operate a power generation unit divided by its total output
Unit	€
Stakeholders in Charge	Network operators (DSO/TSO), Electric utilities, Prosumers and Consumers

3.5.7 Opportunity Cost

Opportunity cost C_{opp} is used in the investment decision making and it is equal to the benefits $B_{Alternative}$ which have not been enjoyed due to the selection of an alternative. In other words, the opportunity cost is the difference between the returns from best investment option and the second-best one.

$$C_{opp} = B_{Alternative} \tag{13}$$

Table 45: *KPI for Opportunity Cost.*

Name of KPI	Opportunity Cost
Description	Benefit that could have been enjoyed if an alternative investment would have been chosen
Unit	€
Stakeholders in Charge	Network operators (DSO/TSO), Electric utilities, Prosumers and Consumers

3.5.8 Investment Risk

High volatility of electricity prices and uncertainty in the future market design and regulation policies lead to a higher risk associated with the investment in renewable generation technologies. Hence, investors require responsive strategies taking into consideration the risk associated with the investment in order to ensure the profitability of their investment.

The investment risk will be measured in terms of the Conditional Value at Risk (CVaR). In literature, Value at Risk (VaR) and Conditional CVaR are mainly used to measure the risk by assessing the probability of losses (Rockafellar & Uryasev, 2000). CVaR, which is an extension of VaR, is often used to assess the probability of a portfolio incurring large losses by evaluating the likelihood (at a specific confidence level) that a specific loss exceeds the value at risk. The VaR_α of a portfolio is the lowest amount such that with probability of α the loss will not exceed the given amount. $CVaR_\alpha$ is the conditional expectation of losses exceeding that amount. In other words, the $CVaR_\alpha$ of profit π is the expected loss if one's interest is restricted to the lowest $100\alpha\%$ of returns. If the profit π has a cumulative distribution function $F(\pi)$ and a probability density function $f(\pi)$, then $CVaR_\alpha(\pi)$ is defined as is shown in the equation 14.

$$CVaR_\alpha(\pi) = -\frac{1}{\alpha}\int_{-\infty}^{F^{-1}(\alpha)} \pi f(\pi) d\pi \tag{14}$$

Table 46: KPI for Investment Risk.

Name of KPI	Investment Risk
Description	Estimation of associated risk for the investment by considering the uncertainties
Unit	€
Stakeholders in Charge	Network operators (DSO/TSO), Electric utilities, Prosumers and Consumers

3.6 Social KPIs

3.6.1 Unemployment Rate

The unemployment rate is a common social KPI which can be of interest in publicly available grid infrastructure. Within HYPERRIDE main applications are commercial areas and campus grids where this number might give a wrong impression on the overall situation.

Table 47: KPI for Unemployment Rate.

Name of KPI	Area's unemployment rate
Description	Residents unemployed as a share of all econonmically active residents
Unit	percent
Stakeholders in Charge	Consumers, institutions

3.6.2 DER Acceptance

The main purpose of this KPI is to find out the acceptance of the policy for DER installations. This means it does not reflect the general opinion towards DER itself but merely how this is handled by policy makers. The measure for this factor is the Likert scale.

Table 48: KPI for DER Scheme Sensibility

Name of KPI	DER scheme sensibility
Description	Are consumers satisfied with the DER policy?
Unit	Likert scale
Stakeholders in Charge	Consumers, institutions

3.6.3 DC Acceptance

The aim of this KPI is to assess the acceptance of this rather new approach among consumers and ultimately comparison with established AC solutions. The result might be affected by information, positive experience and general acceptance of new technologies.

Table 49: *KPI for DC Acceptance.*

Name of KPI	DC scheme sensibility
Description	Are consumers satisfied with the DC approach?
Unit	Likert scale
Stakeholders in Charge	Consumers, institutions, market operators

3.6.4 Landscape Impact

The landscape impact is relevant for all large scale infrastructures. Lines and converter installations might be visible and have negative optical appearance. To quantify the impact of DC as a grid measure, it is important to try to distinguish between asset which would be in place in any case (e.g. wind turbines, PV) from solution related impact (e.g. converters, solid state substations). The base unit is Likert scale and both questions might be assessed with proper generation of the questionnaire.

Table 50: KPI for Landscape Impact.

Name of KPI	Degree of lanscape impact
Description	Measrues potential opposition from citizens and customers based on visual impression. Installed asset may look ugly or obstruct the view to the horizon. An aesthetical measure.
Unit	Likert scale
Stakeholders in Charge	Consumers, institutions, market operators

3.7 Legal KPIs

This indicator presents the extent stakeholders see regulations and standards suitable for the upcoming tasks of infrastructure development. The first on is dedicated to DC grids while the others are targeting localised energy infrastructures independent from the enabling technology.

Table 51: KPI for DC Regulations.

Name of KPI	DC and AC/DC hybrid grid legal framework development
Description	The extent to which DC regulation and standards are suitable at EU level
Unit	Likert scale
Stakeholders in Charge	DSO/TSO, institutions, market operators

Table 52: KPI for Local Energy Cpmmunities Framework.

Name of KPI	Local energy legal framework
Description	The extent to which local energy regulation is suitable at EU level
Unit	Likert scale
Stakeholders in Charge	DSO/TSO, institutions, market operators

Table 53: KPI for (Various) Solution Regulations.

Name of KPI	Suitable solution regulation
Description	The extent to which specific solution regulation is suitable at EU level (e.g. storage, V2G, auxiliary services)
Unit	Likert scale
Stakeholders in Charge	DSO/TSO, institutions, market operators

3.7.1 Monitoring and Evaluation

This indicator evaluates the progress with which results and recommendation are transferred to legal frameworks. The faster adaption takes place the earlier interoperable solutions are available for the benefit of grid stakeholders.

Table 54: KPI for Monitoring and Evaluation.

Name of KPI	Monitoring and evaluation
Description	The progress of findings adaption from policies/strategies/projects
Unit	Likert scale
Stakeholders in Charge	DSO/TSO, institutions, market operators

4 Conclusions

The deliverable provides a base description of existing infrastructures taken into account for subsequent demonstration with the HYPERRIDE project. It can be seen that there are two main regions of interest, namely East Asia (China, South Korea) as well as Europe driving DC grid innovations. Most recent use cases are very use case specific (e.g. Finland use case) but still provide good insight on base need for the project's demonstration sites.

For a deeper understanding of the envisioned installations within HYPERRIDE all three demonstration sites (Germany, Switzerland, Italy) have been described showing fundamental differences in the main purpose and consequently in the grid topology, where the Terni case is more focused on customer related installations (DSO), while Aachen and Lausanne provide laboratory backbones and research testbeds.

The differences in the above mentioned use cases including preexisting demonstrations led to a equally wide set of KPIs formulated to assess DC and hybrid ACDC grid performances. Consequently, not all indicators can be used by all sites but rather a subset will be selected in the subsequent work. It is important to note that it was a clear aim of the project team to lever on existing definitions used for AC grids. Those indicators have been developed throughout the last decades and are well accepted in industry. Adaptions, redefinitions were made if applicable and new ones were defined if needed.

This report is to be used in context of D2.2 (Use Cases) and D2.3 (Enabling Technologies) to gain a full picture of the activities in the project.

The KPI selection will be exploited by the WP related to pilots, namely WP6 (Swiss pilot), WP7 (German pilot) and WP8 (Italian pilot) aiming at linking the proposed KPIs to the operation in the field, taking also into account the nature of the pilot.

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