Smart grid lab research in Europe and beyond

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Summary
In this survey, the objective is to identify current trends in the smart grid research by exploring the work carried out in numerous smart grid labs worldwide. For this purpose, a large number of smart grid labs are identified, and a short description of their activities is given. Fifty-eight out of the 75 identified labs are located in Europe. Smart grid research is divided into categories, which represent popular topics of research in the field. The predominant category of research is identified to be generation and distributed energy resources (Gen & DER) with 91% of the labs conducting research in this field. Aggregated information is presented regarding the labs, providing a clear idea of the topics of research carried out. Connections between different topics of research are presented, which reveal synergies or collaboration gaps among various smart grid topics. Grid management and Gen & DER and energy storage and Gen & DER have been found to be popular combinations of topics with 55 labs active in both, respectively. In addition, we provide insights on the entities at which research is targeted and consider the evolution of publications produced by the labs on the different categories. An overall increase in publications was observed over the past 11 years in virtually all categories of smart grid research with the most published scientific papers in Gen & DER and electromobility. Collaborations between research institutes have been analyzed, pointing out existing joint research conducted and the huge potential to explore synergies between institutes further. Our work is useful in order to identify the smart grid areas where research is focusing on. This gives a clear picture of potential synergies between labs for knowledge sharing and enhancing their research efforts.

KEYWORDS
demand response, electromobility, energy storage, ICT, smart grids, smart homes, smart meters

1 INTRODUCTION

In the last couple of decades, there is a constant increase in energy demand, along with a growing trend toward renewable energy sources (RESs), which introduce alternative ways of energy production. These two characteristics indicate that the traditional grid needs to be modernized, to become ready to cope up with the latest technological demands in a more effective way. The usage of RES is vital, since it leads to a reduction of CO2 emissions, thus contributing to the corresponding European strategic long-term vision for a prosperous, modern, competitive,
and climate neutral economy. On the other hand, complexity has been added to the grid, since the generation using such sources has great variation with time. Improving energy efficiency and energy management also contributes to lowering the overall carbon footprint. All the above can be handled by the modern smart grid, since it can accommodate renewable energy sources in the most efficient way and it can enable a high-class energy management through automated control and modern telecommunication technologies. A smart grid implies that a huge amount of information will need to be handled and controlled. The renewable sources require a constant control and a correct management for an appropriate allocation of energy to take place. In general, the operation of the whole grid needs to be more efficient, real-time responsive, and agile, in terms of energy generation, transmission, and distribution. For this reason, the role of novel technologies used in the smart grid is of vital importance.

In the following, we present the literature review of the related work and the policy context of smart grid lab activities, and we outline the scope and benefits of the current survey, which concludes Section 1.

Section 2 gives general definitions and background on smart grid components and research categories. Sections 3 and 4 present the added value of this review paper, where a description of the activities of each lab is presented in Section 3 and a sum up of the focused research categories of the 75 labs is presented in Section 4. Section 4 extends to include information about linked topics of research, publications, and collaborations of institutes and a discussion on challenges with respect to environmental issues, market needs, infrastructure, and innovative technologies and communications, which can be linked to smart grid research efforts. Finally, a short summary of the main findings and conclusions is presented in Section 5.

1.1 Related work

In recent literature, there are numerous articles surveying on different aspects of smart grids. Molzahn et al. present a survey of distributed algorithms for power systems control. In Hernandez et al., a survey is presented on electric demand forecast models. El-Sayed et al. focus on a survey regarding cloud computing and edge systems, whereas Bera et al. present a review of different cloud computing applications for smart grids. In Li et al., a survey is presented with respect to data analytics techniques used for treating big data of smart grids and electric vehicles (EVs), focusing on the integration of EVs into smart cities. An economic models review with respect to EV charging systems is presented in Shuai et al. where great focus has been given on security issues. Tan et al. show a review of security issues on smart grids with emphasis on the weaknesses of smart grid data. Komninos et al. present a survey of security of smart grids and the smart homes, whereas in Asghar et al., a review of smart meter data usage and privacy techniques is shown. Cybersecurity issues for smart grid communication are the survey topic of He and Yan, where the focus lies on cyberattacks.

As for smart grid laboratory surveys, Cintugulu et al. present a survey with respect to smart grid cyber-physical test beds mainly in the United States. The paper gives a good idea of smart grid research fields, but it mainly focuses on test beds in the United States. In fact, only four out of the 37 test beds presented are outside the United States. In this work, we present the situation of smart grid laboratories around the world, with a focus mainly on Europe.

In general, there are other initiatives gathering information about smart grid labs. For instance, DERLab has gathered information about smart grid labs, with which collaboration has been held, in a database. Some of the laboratories included in that database are also studied in this work; however, more institutes are surveyed, giving a clearer and more complete overview.

In Andreadou et al., aggregated information is presented with respect to the research activities of smart grid labs in Europe and beyond. Information about smart grid tasks and budget issues is collected through an online questionnaire, whereas confidentiality is maintained, especially with respect to budget topics. Although the report gives a good insight into the situation overall and it provides details about the standards and protocols used for each technology, it only presents aggregate information in terms of the number of labs conducting research on a certain category or the number of labs using a specific standard, while information about which lab focuses on a specific technology or a specific smart grid activity is impossible to be retrieved. Unlike Andreadou et al., in this review paper, we present a short description of the smart grid activities of each lab based on publicly available data. This way, our work contributes to identifying labs, which can potentially collaborate. Furthermore, based on the activities of these 75 labs, we present the links between different categories, showing possible dependencies among smart grid fields of research, thus showing current trends. In addition, this paper presents the trends in smart grid research as a result of publications in different categories. Collaborations among the biggest institutes are also presented. For this purpose, thorough research has been conducted based on publicly available data for all the examined institutions. All of the above summarizes the contribution and added value of this review paper.

1.2 Policy context of smart grid lab activities

There is a high correlation between laboratories’ activities and policy. This can already be traced through the national
and international funding mechanisms, which drive the research toward areas of policy interest. The Smart Grid Outlook 2017 shows that there are around 950 smart grid projects initiated within Europe only. It has identified the domains of interest by tracking that 80% of total investments in projects in Europe are related to smart network management, demand-side management, and integration of distributed generation and storage. These are exactly the areas that attract mostly the interest of laboratories too and strongly connected with policy like the Electricity 2019/944/EU and Gas 2009/73/EC Directives, the Energy Union Strategy, the Clean Energy for All Europeans Package, the standardization Mandate M/490 on smart grid standardization, and Calls in Horizon 2020.

The key priorities for the European Commission with the clean energy for all Europeans package are energy efficiency first, the EU’s global leadership in renewables, and a fair deal for energy consumers. This can only be enabled through intensive research, which is carried out in the laboratories. The inventory has clearly shown that key priorities of this Winter package are becoming also key priority areas of research for laboratories putting in the highest positions of their activities the demand response, energy storage, electromobility, smart metering, distributed generation, distributed automation, and smart homes.

Funding mechanisms reinforce and drive the laboratories to activities closely related to policy needs. Specifically, the DT-ICT-10-2018-19 supports interoperable and smart homes and grids call with the H2020 supports laboratories activities toward research on the decentralization and digitization of energy production, the integration of RES, and the promotion of energy efficiency through smart homes, smart buildings, smart communities, and batteries and EVs. The objective is to exploit the potentials of novel services including DR and energy management, which enable the integration of digital technologies in the energy sector. In our study, it was observed that laboratories that are performing research for smart grid issues like demand response and advanced metering infrastructures also involve information and communication technologies and cybersecurity activities, which shows that research activities focus on the integration of various sectors as energy and communications, making them attractive to funding schemes. On the other hand, in the recast of the electricity directive “Directive of the European parliament and of the Council on common rules for the internal market for electricity,” it has been identified that although there is an active involvement of the consumers in generation, storage, and management of the electricity consumption, the design of the retail market prevents to fully exploit their potentials. This was also traced in our study and is discussed later. There is a weak connection between laboratories’ activities related to market and demand response, which reflects exactly the concerns of the recast.

Laboratories’ activities follow the European policy needs and also constitute a valuable tool for identifying the technological gaps and guiding future funding programs.

1.3 Scope and added value of the paper

In this paper, we perform a survey with respect to smart grid research conducted by labs in Europe and beyond. We provide a short description of 75 labs worldwide, and we present the areas of their research. In addition, we present an overview of the focused activities, showing which ones are the popular fields according to the number of labs (out of the total 75) that conduct research on a specific field. Furthermore, we show dependencies between different categories. In addition, we show the trends of smart grid research as these are formed according to publications and collaborations based on publicly available data. The main contributions of our work are summarized as follows:

- It gives a general overview of the existing smart grid research laboratories and their areas of activities.
- It presents the trends in smart grid research, by identifying the most popular smart grid categories.
- It shows dependencies among smart grid categories, showing how likely it is that a specific lab performs research in two different but linked fields.
- It presents the developments of the surveyed 75 labs in terms of research trends over the last years, by giving the trends as these are revealed by publications and collaborations of publicly available work.
- It facilitates identifying scientific groups that perform research on a specific topics of interest, thus promoting possible collaborations.
- It reveals some collaboration links among smart grid laboratories, identified through common publications in the smart grid area.

2 SMART GRID RESEARCH CATEGORIZATION: GENERAL DEFINITION AND BACKGROUND

In this section, we present a categorization of smart grid research, whereas a general definition and background are given for each one of these categories. These categories are, namely, distribution automation (DA), grid management (GM), energy storage (ES), market (MA), generation and DER (Gen & DER), electromobility (EM), smart homes/buildings (SH), smart cities (SC), demand response (DR), information and communication technologies (ICT), cybersecurity (CS), and advanced metering infrastructure (AMI). We use the categories further in our
research presented in Sections 3 and 4 in order to show on which topics the 75 smart grid labs focus. It should be noticed that most of the labs have been found to work on multiple categories.

The categorization of the smart grid research is indicative; however, it can be considered that it gives a good picture of overall research on smart grids and it represents the functionality of different smart grid components and their interconnections. Figure 1 shows a general representation of a smart grid and how its components interact with each other.

The various components and possible links to each category are shown in Table 1. The association of components and categories is indicative, as many of the components play a vital role for more than one category. Categories like smart cities and market are considered as more generic, and their visual representation is difficult; in any case, they are vital fields of research in the overall smart grid research topic.

2.1 | Distribution automation (DA)

This category refers to the automatization of the grid, meaning control and monitoring systems that improve the system’s reliability and power quality. Digital sensors, switches, and intelligent electronic devices (IED) are used for this purpose. Functions like voltage monitoring, reactive power management, volt-Var control and fault detection are performed with DA and GM, which improve the network stability and reduce costs.25

2.2 | Grid management (GM)

Grid management enhances the performance of transformers and other components to facilitate the integration with transmission systems. The main topics covered are substation automation; automation of distributed networks; inverters; self-healing networks; real-time monitoring of the grid; advanced control systems; and microgrids. The research objectives sought in this area include reliability; integration of distributes generation; efficiency; voltage control; and reactive power.

2.3 | Energy storage (ES)

Energy storage includes the process of converting electrical energy in a form that can be stored and delivering this energy in the form of electricity back into the grid when required. Different technologies can be
used for this purpose, whereas the electrical energy can be delivered to the transmission or distribution grid or at customer premises. Storage is very important for the development of smart grids, since it can allow higher integration of renewable energy generation, which is characterized by intermittency. Storage can contribute to a more efficient energy management and can minimize the energy waste. Possible energy storage system types can be among others: batteries, pumped-storage hydroelectricity, underground thermal ES, compressed air ES, thermochemical, chemical-hydrogen storage, flywheels, supercapacitors, and superconducting magnetic ES.26

2.4 | Market (MA)
Market activities are related to the impact of smart grids on the electricity markets, and they can also include the requirements of designing a product for the market. Technological market barriers in smart grids are also considered as well as modeling of new financial frameworks and market relations between actors in smart grids.26

2.5 | Generation and distributed energy resources (Gen & DER)
Distributed energy resources (DER) can be sources of generation and/or storage that are connected to the distribution system. Issues like nonradial power flow and increased fault current duty may occur, and they need to be dealt with. The generation can be categorized in two types: classic generation (dispatchable) and generation that is not controlled by the system operator. Wind energy and solar energy produced by photovoltaics (PVs) are typically produced by DER. Energy from DER is considered vital for smart grids in order to decrease the CO2 emissions and produce energy in an environment-friendly way.27 Further examples of DER are, among others, biomass, hydro fuel cell, tidal waves, or gas power plants.

2.6 | Electromobility (EM)
The concept of EM does entail not only electric vehicles and their usage but also their interaction with the power grid, for which communication infrastructure is important. The topic of EM is vast, and it can cover several aspects, like energy efficiency, power quality, energy management and vehicle autonomy, ES, interoperability, citizen behavior, security and safety, grid load impact, and environmental impact. Vehicle charging is a very important element, and special focus has been given on charging technologies, charging plugs, charging power options, and charging infrastructure.28

2.7 | Smart homes/building (SH)
Smart homes/building implies that modern telecommunication and automatized systems are employed within homes to monitor and control smart devices, whereas communication with smart meters is enabled. Thanks to these advanced systems, the consumer is enabled to become more aware of their consumption and become an active player in the realization of smart grids. Incentives to shift or curtail loads are given, which can be based, for example, on different tariffs. Sensor or submeter networks can also be realized under this category especially within smart buildings, which enable an efficient energy management.26 Activities under this category can be, among others, temperature control, lighting, sensors technology, power quality, smart appliances, DR, and energy management strategies.

2.8 | Smart cities (SC)
Smart cities have attracted the scientific interest lately with several initiatives and leading proposals, like EU SC partnership marketplace29 and the SC research cluster.30 The SC concept entails advanced services to citizens like transportation, lighting, internet access, or other technologies that improve the quality of everyday life.

2.9 | Demand response (DR)
In a broader sense, DR is the initiative to involve all citizens in becoming more active in better energy management. DR implies load shifting or curtailing in order to avoid peaks in the overall consumption curves. This would lead to a more stable and reliable grid. DR can entail tariff incentives to the customers, and it means the intentional modification to the usual consumers’ patterns of electricity usage. It is a topic under investigation lately, with 346 competitive projects in Europe, where topics like baselining, product design, measurement and validation activities, and market models are being addressed.15 Activities involved in DR can include, among others, SH and smart building, demand modeling, DR management systems, and customer energy management systems.31

2.10 | Information and communication technologies (ICT)
Information and communication technologies solutions include all the hardware, software, telecommunication equipment, and systems that enable information transmission among the various actors of a smart grid. This topic includes a vast field of technologies and applications. There are various types of networks (eg, WAN, FAN, NAN, LAN, and HAN), on which smart grid information and communication technologies can be applied. In addi-
tion, there is a plethora of wireless technologies that can
be applied, like GSM, GPRS, 3G, LTE, ZigBee, WiFi, and
6LowPAN, among others. There is also a variety of wired
solutions that can be applied, like the power line commu-
nications (NB-PLC and BB-PLC) and optic fibers, among
others. Activities that can be entailed in this category are
remote equipment configuration, system status monitor-
ing, event management, and response automation, just to
name some.26

2.11 | Cybersecurity (CS)

Cybersecurity is crucial for the existence of smart grids,
since the enormous data transmission implies that
advanced techniques should be applied in order to pro-
tect critical information and confidential data, as has
also been highlighted in Section 1. It also includes all the
measures for protection of the communication devices
against unauthorized access or actions that could lead to
alteration or theft of data. Activities related to CS are risk
assessment, risk response, confidentiality and privacy,
authorization, and authentication, to name some.26

2.12 | Advanced metering infrastructure
(AMI)

Smart meters are a key component of smart grids, since
they enable two-way communication between energy
providers and customers and they can contribute to load
consumption control and monitoring.32 Around 200 mil-

2.13 | Other issues considered

In our survey, we also focused on specific infrastructure
used for smart grid research. The usage of a real-time sim-
ulator or other specific instrumentation reveals certain
trends in smart grid research.

3 | SMART GRID LABS
DESCRIPTION

In this section, we give a description of the labs and present
their activities, based on their online presentation and
their publications. It has to be noted that all the labora-
tories conduct extensive research in their respective fields
and thus produce numerous publications.

3.1 | Australia

3.1.1 | Smart Grid Lab, University
of Melbourne

The core elements of the University of Melbourne's smart
grid lab are its real-time digital simulators (RTDS). They
are being employed to investigate the impact of the inte-
gration of large quantities of DER and storage systems
into the grid. Furthermore, different techniques for the
automation of this process and GM are being explored. The
smart grid lab is conducting its research projects in close
collaboration with DSOs and other institutes.34,35

3.2 | Austria

3.2.1 | cyberGRID

cyberGRID is a private company that not only offers con-
sulting services to its clients but also conducts research in
the area of smart grids. They do so in collaboration with
various partners ranging from industry to research organi-
zations and universities. cyberGRID’s main expertise lies
in ICT, but they also contribute to projects concerning the
integration of DER, storage, DR and EV into the grid, and
GM and AMI services, which extends to the application in
SH and SC.36

3.2.2 | Smart Electricity Systems
and Technologies Laboratory, AIT Austrian
Institute of Technology

The Smart Electricity Systems and Technologies
(SmartEST) Laboratory of the AIT (Austrian Institute
of Technology) consists of two high bandwidth grid
simulators, three independent lab grids equipped with
emulations of loads, control systems, and different line
impedances. Further, the lab has on its dispose a PV array
simulator and is able to conduct hardware-in-the-loop
(HIL) experiments.37 With this range of facilities, they are
able to conduct research in the fields of DER integration,
GM, AMI, DR, ES, EV, SH, and SC.38 Additionally, the lab
is also working on markets, ICT, and CS.37

3.3 | Belgium

3.3.1 | PV Department, IMEC

The research institute IMEC based in Belgium is especially
active in the areas of digital technologies and nanoelec-
tronics. One of IMEC’s expertise lies in the area of solar
energy, and their smart grid expertise is aiming to improve
the efficiency, production, and storage of (solar) energy.
The planning, deploying, and management of smart grids
are thus focused on the automation of solar energy distri-
bution as well as the integration of storage systems into a
smart network linked with PV.39
3.3.2 | EnergyVille, KU Leuven, VITO, IMEC, and UHasselt

EnergyVille was founded as a collaboration between KU Leuven, VITO, IMEC, and UHasselt to conduct research in the area of intelligent energy systems and sustainable energy. EnergyVille is home to 14 laboratories and additional external labs, which include three battery labs, several PV labs and labs dedicated to smart distribution grids, DC distribution systems and smart infrastructure, and an SH lab. As EnergyVille has a strong interest in PV technologies, their expertise extends to the integration and distribution of PV into the electric grid and especially into buildings. SH are among EnergyVille’s core areas of research with a special focus on various storage technologies, EV, and opportunities for demand-side management, which aim at employing these technologies.

3.4 | Brazil

3.4.1 | NAPREI, Research center in smart energy grids, University of São Paulo

São Paulo University’s research center for smart energy grids, NAPREI, is dedicated to advancing modeling techniques, applied to investigate the integration of DER into the electricity grid, the needs for sophisticated monitoring and management, and the accompanying ICT implications. Furthermore, NAPREI maintains strong partnerships with the industry pushing to further real-life prototypes in cooperation with Eletropaulo.

3.4.2 | Laboratory of Intelligent Electrical Networks, Department of Systems and Energy, School of Electrical and Computer Engineering, University of Campinas

Laboratory of Intelligent Electrical Networks (LabREI) of the University of Campinas in Brazil is a lab dedicated mostly to investigating the integration of renewable DER into the electric grid and the challenges linked to the need for novel infrastructures, control, and management of the grid under these conditions. Besides the physical low-voltage network equipped with different sources and programmable loads as well as a communication network, LabREI is developing an internet platform that allows external control and monitoring of the entire system.

3.5 | Canada

3.5.1 | Center for Urban Energy, Ryerson University

The Schneider Electric Smart Grid Laboratory (SESG Lab) is a testing facility within the Centre for Urban Energy (CUE), an industry-academic collaboration between the University of Toronto and the founding partners, Hydro One, the Independent Electricity System Operator, and Toronto Hydro. The industry-oriented research conducted at SESG Lab is focused on the generation and integration of DER through advanced distribution management systems and AMI, which allows to study SH systems in real time. Thanks to the grid-connected utility-scale battery facility of the University of Toronto, fruitful research on ES and the interconnections with smart grids is being conducted jointly in the two laboratories.

3.5.2 | Energy Systems and Nuclear Science Research Centre, University of Ontario’s Institute of Technology

The Energy Systems and Nuclear Research Centre (ERC) of the University of Ontario is home to various smart grid research efforts. The main focus lies on intelligent modeling and simulation tools that improve smart grid operation and enhance the integration of various DER. Their smart control systems are further applied to the energy management in SH and buildings. ERC aims to improve the resilience of systems through real-time fault simulations and is actively involved in grid planning.

3.5.3 | GRIDSIM Power Lab, Kinectrics Inc

Kinectrics is a Canadian company active in testing, inspection, certification, and consulting and home to various laboratories. They are about to extend their repertoire and launch the GRIDSIM Power Lab, dedicated to power system, renewable energy, and smart grid research. The goal is to inform DSO and utilities about the challenges for the network infrastructure related to increased connection of DER and ES systems and to conduct research on control strategies employing advanced ICT technologies. A state-of-the-art RTDS facilitates power hardware in the loop studies.

3.5.4 | Optimization for Smart Grids, Polytechnique Montreal

The research initiative Optimization for Smart Grids (OSG) was founded by a consortium of research institutes and the Polytechnique Montreal and is focused on the application of mathematical optimization techniques to the planning and operation of modern power systems. In particular, the areas in which the initiative is conducting research are system load management and DR, modeling, management and operation of smart buildings, maintenance scheduling in hydropower systems, location and pricing of EV charging stations, and the optimal provision of reactive power in a large-scale grid.
3.6 | Cyprus

3.6.1 | Research Center for Sustainable Energy (FOSS)

The Research Center for Sustainable Energy (FOSS) of the University of Cyprus is active in the research on renewable energies with a special focus on solar energy, their integration into the electricity grid, and the infrastructure it demands in terms of ICT, ESs, DR, and the automation of distribution of DER in particular in smart buildings. The FOSS is home to a Power System Modelling Laboratory (PSM Lab), which is engaging in energy markets, power system analysis, evaluation of power transformers, and the management and control of renewable resource applications, among others.

3.7 | Denmark

3.7.1 | Smart Energy Systems Laboratory, Aalborg University

The Smart Energy System Laboratory (SES Lab) of the Aalborg University is equipped with a real-time discrete simulator to perform hardware in the loop testings among others, as well as emulators for storage facilities, loads, controllers at different levels, communication networks, and distributed generation. The research of Aalborg University extends to the area of SH, SC, and CS and is covering virtually all aspects relevant to the transformation of the power market and the power network toward smart grids.

3.8 | Finland

3.8.1 | VTT Technical Research Center of Finland Ltd

VTT Technical Research Center of Finland is a governmental nonprofit institute, which is conducting multi-technological research and provides innovation services to partners in the industry. VTT's EU-funded Multipower Laboratory (MP-Espoo) is equipped with a fully functional network that comprises production, control, and loading and that can be operated in island or grid-connected mode. It is equipped with diesel generators and a PV system, a local control system, and controllable loads. The multipower lab also accommodates a battery testing facility equipped with a climate chamber and experimental settings to conduct lifetime tests and EV charging and discharging tests under simulated driving conditions. VTT investigates the integration of generated DER, the automation, control, and management of the same, and the integration of ICT solutions.

3.9 | France

3.9.1 | L2EP Laboratory of Electrical Engineering and Power Electronics, University of Lille

L2EP lab is home to the power system research group, which engages in various areas relevant to the transition of current electricity systems to smart grids. In particular, L2EP focuses on the management of electricity systems with respect to objective methodologies, and they investigate the high penetration of power electronic converters in transmission systems. Moreover, real-time modeling and simulations extend their experimental portfolio as well as their work on the control of HVDC transmission systems. In cooperation with their power electronics group, they investigate ES systems and their application in smart grids in general and supercapacitors in particular.

3.9.2 | Procédés-Matériaux-Energie Solaire, Centre National de la Lecherche Scientifique)

The Procédés-Matériaux-Energie Solaire (PROMES) laboratory is part of the French National Centre for Scientific Research (CNRS) and associated to the University of Perpignan via Domitia. PROMES' core research efforts are in material science and solar energy, while they also actively contribute to advancing the knowledge in energy transformation, storage, and transport as well as energy networks. Within their Department of Electronics, Automatic Control and Systems, they engage in the instrumentation, modeling, and control of renewable energy production and storage as well as the improvement of the interface between the electricity grid and DER through improved control systems. A special focus lies on the resource and energy management in buildings.

3.9.3 | PREDIS, Grenoble Electrical Engineering Laboratory

PREDIS is the smart grid platform of Grenoble-INP, which is dedicated to education, research, and technology transfer regarding smart grids. PREDIS is collaborating closely with the Grenoble Electrical Engineering Laboratory (G2ELab). Among others, PREDIS includes an experimental distribution generation and storage platform, an experimental distribution network platform, a smart building used in real conditions, an energy supervision platform for promoting energy management at a global scale, and a simulation platform, which features a real-time simulator applied for hardware in the loop testing.
3.9.4 | EDF Power Networks Lab, Electricité de France

The large French utility EDF’s research facility EDF Power Networks Lab consists of several facilities of which the concept grid is solely dedicated to investigating smart equipment and solutions. A fully functional physical smart grid is complimented by an extended simulated grid, which is connected to sample households that are equipped with charging stations for EV, PV panels, and micro-wind turbines. This infrastructure allows EDF to conduct research on the integration of DER, storage systems, EV, DR, and smart GM including smart metering. Further interests include ICT and CS.

3.10 | Germany

3.10.1 | SmartGridTecLab, Technical University Dortmund

SmartGridTecLab is an academic institute of the Technical University (TU) Dortmund, which maintains close cooperation with the industry. The focus of SmartGridTecLab lies on the simulation of power distribution systems and EM. Their facility includes, among others, a configurable low-voltage network, OPAL-RT and dSPACE real-time systems, electric vehicles, power amplifiers, MV/LV transformers, battery storage, PV inverters, configurable loads, and corresponding measurement devices.

3.10.2 | Institute for Automation of Complex Systems, RWTH Aachen

The Institute for Automation of Complex Systems (ACS) is jointly hosted by RWTH Aachen and the E.ON Energy Research Center and an interdisciplinary research institute. Their core interests related to smart grids are ICT, grid operation, control, and automation. Their modern control architectures contribute to improved integration of DER and storages into the grid while also, protection techniques and CS are implied. Electrical distribution and usage in SH and SC including DR and EM are further research topics pursued by ACS. The research facility is equipped with sophisticated hardware and software to conduct real-time simulation and HIL testing.

3.10.3 | SENSE Smart Grid Lab, TU Berlin

In the SENSE Smart Grid Lab of TU Berlin, research is conducted on the integration of different forms of energy and high proportions of renewable energies into a single grid through an integration of AC, DC, and ICT networks. The operational challenges of a smart grid are being investigated with respect to the roles that electric vehicles, different storage concepts, and DR may play. The facility comprises a fully integrated microgrid that connects a PV and a wind power simulator, smart buildings, several EV charging stations, an ES system, and a central management and control unit. With a real-time simulator, it is possible to simulate the transmission grid and its impact on the microgrid in the lab through HIL testing. Furthermore, TU Berlin is maintaining a battery test stand, where the charging and discharging of electrical ESs can be investigated under different conditions.

3.11 | Greece

3.11.1 | Electric Energy Systems Lab, National Technical University of Athens

The National University of Athens is home to the Smart Grids Research Unit of the Electrical and Computer Engineering School (Smart RUE), which belongs to the Electric Energy Systems Laboratory (EESL). Smart RUE is studying the flexible coupling of power electronics configuration for coupling DER and storage systems; in order to do so, they can take advantage of their in-house PV and wind systems. Additionally, EM lies within the focus of this institute as well as low-voltage grids operated by multiagent systems. Smart grid controllers and other hardware are tested using their power-hardware-in-the-loop (PHIL) simulation environment and their controller-hardware-in-the-loop (CHIL) simulation environment.

3.11.2 | Microgrid and Distributed Energy Resources Laboratory, Centre for Renewable Energy Sources and Saving

The Greek Center for Renewable Energy Sources & Saving (CRES) is home to multiple research facilities, among others, the Microgrid and Distributed Energy Resources Laboratory. CRES’ microgrid is used to study stand-alone or interconnected grids, where various DER are interconnected and controlled as well as storage systems (chemical and electrochemical) and demand-side management. Besides the physical components and the implicated control system, there is an ICT interface that is also tested in SH. Furthermore, CRES is conducting grid simulations for different scenarios of RES penetration in distribution grids.

3.12 | Ireland

3.12.1 | Integrated Energy Lab (IE Lab), University College Dublin

The Integrated Energy Lab is part of the University College Dublin’s Energy Institute. IE Lab was founded through a partnership with the Electric Power Research Institute (EPRI) and in collaboration with industrial partners of the Irish energy sector. The facilities include renewable energy generation systems, energy saving systems, energy monitoring, and building management systems. Relying on
these, IE Lab has competences in the areas of technology integration assessment and interoperability, system performance evaluation, model validation, prototyping, and advanced communication infrastructures.72

3.13 | Italy

3.13.1 | ABB Smart Lab, ABB Ltd

The energy and automation company ABB, Italy, is maintaining a smart grid lab, dedicated solely to smart grids. ABB’s facility is equipped with state-of-the-art systems including distributed network components as current and voltage sensors, medium- and low-voltage switchgear, protection relays, and a monitoring system. Additionally, there are inverters in place in order to include ABB’s PV plant. The simulation model employed within the ABB Smart Lab, developed in cooperation with the Polytechnic of Milan, allows to simulate the behavior of electrical distribution networks, components, and systems in home automation systems, data centers, management of installed systems, and energy efficiency.73

3.13.2 | Smart Grid Interoperability Lab, Joint Research Centre, European Commission

The Smart Grid Interoperability Lab (SGI Lab) of the Joint Research Centre (JRC) of the European Commission performs research in a wide range of smart grid topics, including DR, AMI, ICT, EM, ES, GM, and DA. Special focus is given on interoperability, which is fundamental for modern smart grid systems. For this purpose, the interoperability testing methodology has been developed and is followed in the lab experiments.74 A real-time simulator is also used for simulating the distribution grid. In addition, experiments regarding the integration of electric vehicles to the grid are also carried out.75

3.13.3 | EPIC, Joint Research Centre, European Commission

EPIC focuses on CS issues, ICT, and AMI. Experiments are carried out on specific test beds examining communication issues and emphasizing on CS issues.26

3.13.4 | VeLA8, Joint Research Centre, European Commission

VeLA8 focuses mainly on EM. Tests on conventional hybrid and plug-in hybrid vehicles are performed under normal or extreme conditions along with fast chargers testing. A climatic chamber is available for tests at a temperature range of −30° C to +50° C.76

3.13.5 | VeLA9, Joint Research Centre, European Commission

VeLA9 and VeLA8 belong to the same unit of the JRC. The main topic of research is EM. An anechoic chamber is available for assessing the electromagnetic compatibility and interferences of electric vehicles and their charging infrastructure.

3.13.6 | Distributed Energy Resources Test Facility, Ricerca sul Sistema Energetico SpA

Ricerca sul Sistema Energetico (RSE) is a research institute owned by the Italian utility company Gestore dei Servizi Energetici GSE. The RSE is home to the Distributed Energy Resources Test Facility (RSE DER-TF), which is equipped with a fully functional low-voltage smart grid that comprises distributed generators, different storage systems, EV charging stations, and loads. The possibility of reconfiguring the type of network guarantees a great operational and experimental flexibility of the system. Besides the testing of technological appliances, the smart grid is used to develop and test GM and automatic control techniques that explore, eg, DA and demand-side management strategies. At RSE, there are further a testing facilities dedicated to energy efficiency and home automation and one, which is invested in CS and power control system resilience.77

3.13.7 | SmartGrid Lab, University of Pisa

At the the Smart Grid Lab facility of the University of Pisa, Italy, various fields related to smart grids are studied in cooperation with national and international research centers. Among the fields of interest are innovative distributed techniques and algorithms for the analysis and optimal management of large-scale complex networks, with particular reference to the modeling of energy networks; optimal management of power flows in microgrids/virtual power plants; the development of forecasting and clustering algorithms to support the integration of electricity production from renewable sources; and the development of functionalities to support the development of hybrid/electric vehicles (algorithms for the management of distributed recharging and routing techniques for saving energy consumption).78,79

3.13.8 | PrInCE Microgrid—Electrical Energy System Laboratory, Politecnico di Bari

At the Electrical Energy System Lab PrInCE of the Politecnico di Bari, an experimental microgrid has been implemented. It combines several distributed energy sources as a CHP, a gas turbine, a PV system, and a wind turbine simulator with storage devices, ie, batteries, EV, and
programmable loads. Through the experimental SCADA control system, different modes of operation and GM can be explored.80,81

3.14 | Latvia

3.14.1 | Smart Grid Research Centre, Institute of Physical Energetics

The Smart Grid Research Centre within the Institute of Physical Energetics in Riga, Latvia, engages in technology research, installation and testing of equipment, energy system management, and modeling. Their main focus lies on the management and dispatch of DER and DR; thus, their expertise extends to SH and smart buildings. They furthermore conduct research on the electricity market, and the challenges and restructuring it will face in the wake of smart grids.82

3.15 | The Netherlands

3.15.1 | Electrical Sustainable Power Laboratory, Delft University of Technology

At TU Delft, an electrical sustainable power lab is being developed, which addresses various aspects relevant to power research ranging from material science, digital infrastructures, to network simulation and modeling. In the smart grid lab within this facility, TU Delft simulates and tests the impact of DER and storage integration on distribution grids and develops models to simulate these impacts on a higher level. In this context, a real-time simulator is installed to conduct hardware in the loop experiments. Another key focus of the lab lies on DC power grids and the integration of PV in particular.83

3.15.2 | Flex Power Grid Lab, DNV GL

DNV GL is an international classification society and accreditation registrar that also offers technical consulting services. Their Flex Power Grid Lab (FPGL) is an independent laboratory located in Arnheim, The Netherlands. FPGL’s expertise lies on DER and renewable energies and their integration into a smart grid and the development of power electronics. Through their real-time simulator, they are able to offer HIL testing for industrial high-voltage components and validation on a system level. Research at FPGL is taking place in close cooperation with seven more laboratories located in the vicinity of FPGL. There are, among others, the Battery Testing Lab, the CS Lab, the Smart Meter Lab, and the Protocol Testing Lab.84

3.15.3 | Smart Grid Home Lab, Joint Research Centre (JRC), European Commission

The Smart Grid Home Lab (SG Home Lab) together with the SGI Lab in Italy belongs to the same unit within the JRC. The two labs complement each other, and collaborations are held. The topics of research include markets, SH, DR, ICT, CS, and AMI. Focus is given on interoperability, similarly to the SGI Lab, and the interoperability testing methodology is followed. The lab entails, among others, SH devices and energy management systems, whereas a real-time simulator is also available.85

3.16 | New Zealand

3.16.1 | Power Systems Group, University of Auckland

The Power System Group of the University of Auckland, New Zealand, is conducting smart grid research in close cooperation with various stakeholders in the power sector, eg, DSOs, TSO, utilities, and policy makers. Their core focus lies on automation and protection, policies, and electricity market research. Furthermore, they engage in the development of advanced ICT techniques and CS programs.86

3.17 | Norway

3.17.1 | National Smart Grid Laboratory, The Norwegian University of Science and Technology

The Norwegian University of Sience and Technology in Trondheim is currently building a National Smart Grid Laboratory in cooperation with the Research Council of Norway. The research to be conducted shall range from the integration of large-scale DER, ES, EV, their management, and automation to the integration of ICT, which includes security, stability, and reliability aspects. In order to do so, a variety of physical assets will equip the laboratory including EV charging infrastructures and SH appliances and smart meters. Furthermore, real-time digital simulators allowing for hardware-in-the-loop testings will complement the inventory of the laboratory.87

3.18 | Poland

3.18.1 | Laboratory of Power Line Communications, Wroclaw University of Technology

Wroclaw University of Technology accommodates the Laboratory of Power Line Communications (PLC). In the PLC Lab, the implementation of ICT through PLC is studied, while the chances for a smart GM and smart metering are being explored. PLC Lab’s focus extends to the issue of CS.88
3.18.2 Distributed Generation Laboratory, Institute of Electrical Power Engineering, Lodz University of Technology

The University of Lodz’s Laboratory of Distributed Generation is equipped with various distributed generation units, such as a microturbine, wind turbines, PV systems, and fuel cells. A SCADA system is implemented in order to integrate, control, and measure the DER as well as the dynamic ES system and the model of loads. Additionally, the lab is equipped with a programmable generator, which runs with a real-time simulator.89

3.19 Portugal

3.19.1 EDP Labelec, Energias de Portugal SA

The EDP Labelec laboratory of the large Portuguese energy utility Energias de Portugal (EDP) is home to sophisticated research facilities in the area of smart metering, SH, ES, and ICT. In particular, EDP Labelec entertains projects on AMI, which they assess on a residential level and they apply their ICT to automate the integration of DER and storages, where their expertise is in supercapacitor storage systems.90

3.19.2 R&D Nester Real-Time Power Systems Simulation Laboratory, Centro de Investigação em Energia, REN-Stategrid SA (R&D Nester)

R&D Nester of the Centro de Investigação em Energia is a research center created through the partnership between REN (REN-Redes Energéticas Nacionais, SGPS, SA) and the State Grid Corporation of China. Their Real-Time Power Simulation Laboratory is equipped with different software and hardware solutions that allow, among others, for HIL experiments and the simulation of power systems and communication networks. This is facilitated through their main assets, which are two real-time power system simulators. The core research focus of R&D Nester lies within the areas of power system simulation, renewable energy management, and energy markets and economics.91

3.19.3 Group of Energy and Power Electronics—Centro ALGORITMI, Universidade do Minho

The Power and Energy Electronics Research Group (GEPE) is integrated in the Industrial Electronics Line of the Centro Algoritmi. The Centro Algoritmi belongs to the University of Minho’s School of Engineering and is active in R&D in the field of ICT and electronics. GEPE is mostly focused on the application of power electronics in power systems. Their main research evolves around the topics of power quality monitoring and conditioners, the interface and integration between distributed renewable energies, and the electricity grid as well as battery ES systems and EM.92,93

3.19.4 Smart Grid and Electric Vehicle Laboratory, INESC TEC—INESC Technology and Science

INESC TEC is a private nonprofit research institute that is entertaining the Smart Grid and Electric Vehicle Laboratory (SG & EV Lab). INESC has developed a great expertise in the field of modeling and simulating networks and power systems, which provides the testing frameworks for physical components and systems. They have recently extended their capabilities to perform PHIL testing, implemented with a real-time simulator that models the power network and a bidirectional three-phase back-to-back (B2B) inverter. Thereby, INESC can test their GM techniques, the automated distribution of DER, and the interplay with storage systems, DR, and EV. Furthermore, INESC’s aim is to develop a platform that will allow for testing of their control and automation system in an SH environment.94

3.19.5 National Laboratory for Energy and Geology

Within the National Laboratory for Energy and Geology (LNEG), research is conducted primarily on the generation of energy with a particular focus on solar energy. The integration of PV into buildings and cities is investigated, and thus, smart GM structures are being developed at LNEG, which are aimed to be integrated with storage and DR options. LNEG’s expertise expands to energy and electricity markets.95

3.20 Russia

3.20.1 Smart Grids Lab, Skolkovo Institute of Science and Technology (Skoltech)

Skoltech, Skolkovo Institute of Science and Technology, has recently opened a smart grid/microgrid laboratory within their Department of Energy Systems. In the lab, there is a fully functional microgrid that can be operated in grid connected and island mode in order to test devices as renewable energy generators, ES systems, smart programmable loads, and different grid control and energy management strategies. The facility is equipped with a PV system and wind turbines, programmable loads, and storage systems (batteries and supercapacitors).96 A real-time grid simulator is in place, which allows to investigate the interaction of the microgrid with the main grid and HIL testing.97
3.21 | Spain

3.21.1 | Instituto Tecnológico de la Energía

The Instituto Tecnológico de la Energía (ITE) is home to different laboratories researching topics relevant to smart grids. The labs include an Interoperability and Communication Laboratory for Smart Devices and Smartgrids, an active demand management lab, an EV charge management lab, a thermal, wind, and PV energy generation lab, and a simulation lab, among others. ITE conducts research on the manageability of domestic charges and the charge characterization of household appliances. They also study and characterize hydrogen batteries and generators and develop a platform for new ES systems. Furthermore, ITE engages in the validation of demand management algorithms, development of ICT solutions with accountant, and distribution operator based on PRIME standard on PLC, the integration and modeling of distributed renewable energy production systems, and the development of power electronics products.98

3.21.2 | Smart Energy Integration Lab, IMDEA Energy Institute

The Smart Energy Integration Laboratory (SEIL) of the IMDEA Energy Institute in Spain is engaged in various topics concerning smart grids. SEIL is active in the development of control strategies for smart and microgrids, energy management for power dispatch, and smart buildings with a special focus on storage management for DR and electric vehicles. Further focus areas are the integration of renewable DER, the testing of power electronic applications, and the real-time simulation of electrical grids and power flows.99

3.21.3 | ATENEA Microgrid Lab, The National Renewable Energy Centre of Spain (CENER)

Within The National Renewable Energy Center of Spain, CENER, there is the Department of Renewable Energy Grid Integration, which is conducting research in the smart grid sector relying on various lab facilities. Within the department, the ATENEA Microgrid Laboratory is dedicated to industrial applications and the evaluation of new equipment through HIL testing, generation systems, ES systems, control strategies, and protection systems. It operates in close collaboration with the Wind Turbine Test Laboratory, and ATENEA itself is equipped with, among others, a PV system, different ES systems, and electric vehicles.100

3.21.4 | InGRID, Smart Grids Testing and Research Infrastructure, Tecnalia

Tecnalia is a privately funded research center, which is home to InGrid the Smart Grid Testing and Research Infrastructure. It is based on several laboratories that focus on different aspects related to smart grids. Thereby, InGRID is covering virtually all topics relevant in the field through their huge capacities. The labs include a power lab, an HV lab, an LV and environmental lab, a power electronics and microgrid lab, an electromagnetic compatibility lab, a smart metering lab, on site-testing lab for the evaluation of equipment, and a facility dedicated to smart grid communications. Furthermore, Tecnalia's facilities include an electrical vehicle network connection, small-scale systems for the generation of electricity from renewable resources, and several ES systems.101

3.21.5 | Renewable Energy Integration Laboratory, CIRCE Research Center for Energy Resources and Consumption

The Research Center for Energy Resources and Consumption, CIRCE, is closely cooperating with the University of Zaragoza, Spain. CIRCE is home to the Renewable Energy Integration Laboratory, where the integration of DER, storage systems, EV, DR, and microgrids into the electric grid is studied, relying on a microgrid facility and EV charging stations.102 A real-time digital simulator is complementing CIRCE’s research facilities.103 CIRCE accommodates a number of other laboratories within which smart grid research is conducted. QuEST Lab, Quality Test for Energy Systems, is a mobile lab used to test the MV network, especially under the impact of increased integration of distributed renewable energy sources.104 Similarly, the MEGHA lab is another portable lab, which also investigates the interface between RES and the electricity network, but MEGHA is fully dedicated to assessing the performance of wind farms.105 The I2SET Lab is dedicated to the automation and smart control of substation systems and the implementation of integrated communication systems.106 Furthermore, the automation and implementation of ICT into the electricity network and the resilience of such networks are studied in the electric protection testing laboratory.107

3.21.6 | Smart Grid Data Communication Laboratory, DNV GL Spain SL

The Smart Grid Data Communication Laboratory (SG DataCom Lab) of DNV GL, Spain, has its main focus on smart metering, as they were strongly involved in the Spanish smart meter roll out and conducted various technical and economic analyses on the project. Besides their smart
meter and market research, they are also involved in ICT infrastructures with a strong focus on CS.108

3.21.7 | “Magic Box,” Universidad Politécnica de Madrid

Magic Box is a net-positive energy building located at the Universidad Politécnica de Madrid, Spain. It is a project aimed at exploring the potential of self-sufficient smart buildings, where integrated PV, ES systems, and smart consumption management and control allow houses to be self-sustained.109

3.21.8 | Grid Integration Laboratory LINTER, Unión Fenosa Distribución, SA

The Unión Fenosa Distribución (UFD), SA, a Spanish electricity distributor, affiliated to the utility company Gas Natural SDG, SA, maintains the Grid Integration Laboratory LINTER in Madrid, Spain. The core focus of the research lies on interoperability of smart meters, low- and medium-voltage grid automation, and the integration of DER and EV into the grid. In order to do so, LINTER is equipped with distributed generation facilities, screened electric and data cables, information-systems testing grounds, EV charging stations, meters cabinets, and communication technologies and services to investigate DR applications.110,111

3.21.9 | UDEX, Ormazabal Corporate Technology

Ormazabal Corporate Technology is active in the areas of electrical networks, electronics, and ICT.112 Ormazabal maintains an in-house smart grid lab UDEX, where they research on network automation, PLC, AMI, demand-side management, integration of DER, EV, and storage systems. UDEX’s facilities include a test bay, underground cable galleries and overhead lines, a control, measuring, and communication center, an MV grid connection, a PV roof plant, wind turbines, an EV charging station, and an ES substation.113

3.21.10 | iSare Microgrid Gipuzkoa, ceit-IK4 (Centre of Studies and Technical Research)/JEMA ENERGY

iSare is a microgrid benchmark project in Gipuzkoa, Spain, jointly run by the research center ceit-IK4, the ICT association GAIA, and the energy technology company JEMA. The microgrid consists of various distributed (renewable) energy generation devices as PV panels, wind turbines, gas microturbine, fuel cells, and diesel generators with a combined capacity of 400 kW. It further includes various storage systems, ie, batteries, supercapacitors, and flywheels, as well as EV charging stations. iSare can be operated in island or grid-connected mode, and load management (including DR) is conducted using advanced ICT systems and smart metering devices.114

3.21.11 | CITCEA Lab, Universitat Politècnica de Catalunya—BarcelonaTech

The technology research center CITEA of Universitat Politècnica de Catalunya (UPC) is active in the areas of renewable energy generation, power electronics, (digital) energy systems, energy economics, and smart grids. Regarding the latter, CITEA especially engages in planning, architectural, and ICT concepts, monitoring, and operation systems, while also, energy efficiency, markets, and regulations are in CINEA’s focus.115-119

3.22 | Sweden

3.22.1 | STRI AB

STRI is a Swedish independent laboratory specialized in high-voltage testing. Various projects conducted in cooperation with, among others, grid companies, utilities, authorities, and universities make up their portfolio. In the area of smart grids, they are active in the development, control, and operation of microgrids and the investigation of different techniques for the integration of DER. Within another project, STRI engaged in the implementation of ICT infrastructures, GM, and the merits to the hosting capacity through the integration of storage systems and DR.120

3.23 | Switzerland

3.23.1 | Distributed Electrical System Laboratory, École Polytechnique Fédérale de Lausanne

The Distributed Electrical System Laboratory (DESL) is the smart grid test facility of the École Polytechnique Fédérale de Lausanne. Above all, DESL is developing models to enhance the management, integration, and monitoring of DER and storage systems, where their focus lies on battery ES systems (BESS); among others, they employ real-time simulations to do so.121 Another focus lies on the integration of ICT into smart grids, in which context CS is a core concern of DESL’s research.122

3.24 | UK

3.24.1 | Smart Grid Laboratory, Durham University

Durham University’s Smart Grid Lab is a well-equipped research facility to investigate the challenges networks are facing in the wake of decarbonization. The lab accommodates a flexible low-voltage distribution network, a real-time digital simulator, a PV emulation system, a wind
turbine emulation system, an electrical ES, an EV charging station, and an air-source heat pump.\textsuperscript{123}

3.24.2  \textbf{Smart Energy Laboratory, Imperial College London}

The Imperial College London is organizing their multi-disciplinary research on smart grids within their Energy Future Lab. Various projects are being conducted in cooperation with other institutes, energy utilities, TSOs, and DSOs. The fields of research include the smart management of grids and DER through demand-side management of consumption and storage systems and the implications for the current and future infrastructure.\textsuperscript{124-126}

3.24.3  \textbf{Power Networks Demonstration Centre, University of Strathclyde}

The Power Networks Demonstration Centre (PNDC) was founded by government, industrial, and academic partners and is associated with the University of Strathclyde in Glasgow. The PNDC facility comprises an LV network and an 11-kV network that is a representative of the UK networks. There physical equipment can be tested under real conditions prior to commercialization as well as innovative control and GM strategies, eg, demand-side management and storage systems. The networks are able to operate in island mode or in grid connection mode, and a real-time simulator can support larger system testing.\textsuperscript{127}

3.24.4  \textbf{Smart Grid Laboratory and ES Test Bed, Newcastle University}

At Newcastle University, the Smart Grid Laboratory (SG Lab) and ES Test Bed research is focused on the simulation of distribution networks. The pivotal component is the lab’s real-time network simulator, which is integrated in an LV network alongside a control system platform. Further, integrate are emulations of PV, variable loads, and storage systems. The lab is also equipped with an EV charging post.\textsuperscript{128}

3.25  \textbf{USA}

3.25.1  \textbf{Future Renewable Electric Energy Delivery and Management Systems Engineering Research Center, NC State University}

The research facility Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Engineering Research Center was launched as a joint project of different universities and industrial partners in 2008. The lab is involved in the entire chain of research activities from simulations, to prototyping, to lab testing, and field deployment. They employ multiple RTDS, Opal RT, and Typhoon HIL simulators. Further, FREEDM is equipped with the infrastructure to test MV equipment up to 15 kV and 1 MW. A PV rooftop system and EV charging stations complete their facility.\textsuperscript{129}

3.25.2  \textbf{EnerNex Corp, CESI SpA}

EnerNex is a CESI company located in Knoxville, USA. The company is active in the electric power industry and provides its consulting services to various players in the industry. Through their in-house research facilities, EnerNex underpins their services. Especially, the effects of renewably generated electricity on the grid and the challenges of managing and balancing fluctuating renewable energies are the core of EnerNex interests. Through sophisticated modeling techniques and simulations, they actively research in the areas of DR, DA, GM, and AMI. With regard to the particular interests, they developed their expertise in CS and ICT.\textsuperscript{130}

3.25.3  \textbf{PENSA, Princeton University}

PENSA is the division for energy system analysis at Princeton University, New Jersey, USA. Their research focuses mainly on mathematical modeling, which is applied, among others, to investigate the challenges and opportunities for smart grids in the face of the energy transition. Their models are employed to advance research regarding the interplay of energy markets and smart grids. Furthermore, the impact of distributed renewable electricity on grid stability, the need for DR and storage systems, and the resulting requirements for appropriate GM are within the focus of the research group.\textsuperscript{131}

3.25.4  \textbf{Center for Advanced Power Systems), Florida State University}

The Center of Advanced Power Systems (CAPS) of the Florida State University is conducting research in virtually all fields relevant to advancing smart grid technologies. CAPS does so by merging physical experiments with simulations. Their 5-MW prototype test facility is providing the hardware that is coupled with the largest real-time digital simulator (RTDS) employed in a smart grid lab. Hardware-in-the-loop tests expose physical devices to simulated testing environments. CAPS advances simulation and modeling techniques and validation of their models under physical test conditions.\textsuperscript{132}

3.25.5  \textbf{FLEXLAB, Lawrence Berkeley National Laboratory}

The Lawrence Berkeley National Laboratory’s FLEXLAB is a lab dedicated to buildings that includes SH. Within this, their FLEXGRID lab is entirely dedicated to SH and smart grids, where they have the facilities to test the integration of PV panels, batteries, and electric vehicles. Through
HIL testing, they expose their programmable inverters to simulated conditions in order to improve power quality.\(^\text{133}\)

### 3.25.6 Irvine Advanced Power and Energy Program, UC Irvine

The Distributed Generation Test Bed of the Advanced Power and Energy Program of the University of California, Irvine, is conducting research on the integration and automation of distributed RES, storage, and EV into the grid. Besides their physical testing facilities, the research extends to the development of models and simulations, eg, to further investigate the interplay of the electricity grid and the transport sector.\(^\text{134,135}\)

### 3.25.7 Smart Grid Lab, Kansas State University

The Smart Grid Lab of the Kansas State University is actively contributing to the development of software and ICT solutions to enhance the management of smart grids and facilitate the integration of DER. Furthermore, their simulation capabilities are applied to address issues related to CS that pose threats to various players along the chain of the power system.\(^\text{136}\)

### 3.25.8 Energy System Integration Facility, National Renewable Energy Laboratory

The Energy System Integration Facility (ESIF) of the major research institute NREL is a highly equipped research laboratory that is contributing to virtually all fields relevant to smart grid advancement. ESIF’s high-performance computing (HPC) system is a supercomputer that is employed to study fully integrated systems on the one hand, and it is employed to perform hardware-in-the-loop tests on the other hand. For the latter, they can resort to test facilities that feature megawatt-scale electricity generation systems to study the integration of DER, storages, and EV. ESIF is furthermore active in the SH and smart building research as well as in the field of microgrids, where they employ network simulator-in-the-loop testing on the one hand and PHIL simulation on the other hand, linking it to their various hardware. Apart from that, there is a working group at ESIF dedicated to the field of CS and resilience, which is offering their services to utilities across the country. Furthermore, ESIF is maintaining relations and collaborations with various players in the industry.\(^\text{137}\)

### 3.25.9 Advanced Power Engineering Laboratory, Colorado State University

The Advanced Power Engineering Laboratory (APEL) of the Colorado State University has a strong focus on the management of (distributed) energy in advanced system infrastructures not only in smart grids but also in particular in the SH and building environment. Therefore, other core areas of research include the integration of storage systems and DR in the residential sector and in microgrids.\(^\text{138}\)

### 3.25.10 Research group on the Advanced Control of Energy and Power Systems, Colorado School of Mines

Colorado School of Mines’ research group on the Advanced Control of Energy and Power Systems (ACEPS) engages in research on intelligent control systems for power systems and power electronics, real-time monitoring and advanced diagnostic systems, artificial intelligence, advanced acoustic, optical and electromechanical sensors, pollution reduction, transformers and breakers monitoring, smart substations, power quality, nondestructive evaluation, advanced power electronics, remote sensing, security, control, and integration of renewable and alternative energy sources into the grid.\(^\text{139-141}\)

### 3.25.11 New Mexico SMART Grid Center, Microgrid System Laboratory

The Microgrid System Laboratory is a consortium of different partners from the industry, research, and academia, which has recently launched a new project, ie, the New Mexico SMART Grid Center. The core areas of research regard the design of distribution grid infrastructures including ICT, which will be done through employing diverse test beds as well as advanced modeling and simulation techniques.\(^\text{142}\)

### 3.25.12 Smart Grid Demonstration and Research Investigation Lab, Washington State University

The Smart Grid Demonstration and Research Investigation Lab (SGDRIL) of the Washington State University is dedicated to the development, testing, and validation of power system operation and control algorithms for microgrids and distribution systems.\(^\text{143}\) SGDRIL is advancing the research on ICT techniques for distribution grid integration and is also engaging in issues related to CS.\(^\text{144}\) They also conduct real-time modeling and HIL simulations.

### 4 SMART GRID LAB RESEARCH

This section presents the sum up of the results of the 75 surveyed labs with respect to their smart grid research. First of all, an overview of the categories of research (as these are defined in Section 2), the labs are active in, is given. A further discussion follows showing the connections between categories of research. In addition, other important aspects are presented, like the entity for which the labs conduct
research and the main activities that the labs focus on. Finally, an analysis of data on the institutes’ publications is presented, which includes information on collaborations between them. It should be highlighted that this section presents collective information about the 75 smart grid labs that have been examined for this work.

4.1 Overview of focused activities

This section quantitatively sums up the focus the labs declare in their webpages and reveal in their publications. The categories of research areas as defined in Section 2 will be the guideline for the descriptive analysis conducted based on the gathered information. Table 2 includes all 75 laboratories and indicates the categories of research they are active in. The information provided in Table 2 makes no claim to completeness.

There are several countries, where merely one or two labs could be identified, ie, Australia, Austria Belgium, Brazil, Cyprus, Denmark, Finland, Greece, Ireland, Latvia, New Zealand, Norway, Poland, Russia, Sweden, and Switzerland. While there are other countries, ie, Canada (four labs), Italy (eight), Portugal (five), Spain (11), the United Kingdom (four), and the United States (12), which are home to a multitude of labs. In general, 58 out of 75 labs identified within the scope of this review paper are located in Europe. Outside Europe, there is one lab each in Australia, New Zealand, and Russia, two in Brazil, and 12 in the United States. There are a minority of laboratories where only a few categories of smart grid research are covered. This is mostly due to their dedication and expertise that is focused on one area of research only. Popular fields to focus completely on are, eg, EM or SH as they can be treated independently. However, the majority of laboratories is active in a variety of smart grid research activities, due to the interlacement of the different research areas in the smart grid context.

Besides the overview on the activities of smart grid labs worldwide, the cumulative picture is provided in Table 3. The percentage of labs among the listed 75 labs that are conducting research in the respective categories is displayed.

The most popular category of smart grid research with 91% of active labs is Gen & DER. There are only a small number of labs that do not work in this area, because they conduct specialized research, eg, only on EM or exclusively on power line communication and ICT. The integration of DER into the grid is one of the major challenges and motivation for smart grid research, which is underlined by the large number of labs active in Gen & DER. This category is followed by DR and GM with 76% each and ES with 75%.

In Figures 2 and 3, the smart grid labs per country are shown, based on the responses to the JRC survey. The size of the circles corresponds to the number of smart grid labs for each country, ie, from 1 to 12. The inner pie chart illustrates the different activity categories, as described in Section 2, where the size of the colored piece for each category depends on the number of labs with activities in this topic. Looking at Figure 1, for example, Ireland has one smart grid lab that has activities in Gen & DER, SH, and DR, whereas in Greece, there are two smart grid labs working on all topics except CS, and there are twice as many labs working on ES than on GM.

4.2 Information analysis: Connection between categories, main activities, and targeted entities

In this section, we give a more detailed picture of the activities carried out by the labs, and we present some information regarding possible dependencies between categories.

An interesting point is the number of categories the labs are active in. Figure 4 shows how many labs are involved in a number of research categories, which depicts the span the labs cover regarding smart grid topics.

It can be observed from Figure 4 that there are a variety in the number of labs working on different categories. The minority of the labs focuses on a small number of categories (up to four categories). A bit more than half of the labs are working at least on eight categories.

It is also worthwhile to consider possible connections among the categories; ie, are there categories that are often jointly in the focus of a single laboratory? Figure 5 shows this kind of dependencies for some categories. In particular, we show how often it is observed that a specific lab works simultaneously or not on the following:

- DA and GM; GM and Gen & DER; Gen & DER and ES; ES and EM; EM and GM; and
- Market and DR; DR and AMI; AMI and SH; SH and SC; AMI and ICT.

Figure 5 presents the number of labs that conduct research simultaneously on these categories and also gives the number of labs that carry out research only on one category and not on the other.

As it can be observed, there is a very strong connection between the categories

- GM and Gen & DER, since 55 labs perform research on both categories, whereas 57 labs in total are active on GM;
- AMI and ICT, with 31 labs performing research on both fields, on a total of 34 labs working on AMI; and
- ES and Gen & DER, where it is observed that there is no lab carrying out research on ES that does not also work on Gen & DER issues.
| Institute/Company                     | Acronym | Categories of Smart Grid Research | DA | GM | ES | MA | Gen & DER | EM | SH | SC | DR | ICT | CS | AMI |
|--------------------------------------|---------|-----------------------------------|----|----|----|----|-----------|----|----|----|----|-----|----|-----|
| Australia                            |         |                                   |    |    |    |    |           |    |    |    |    |     |    |     |
| The University of Melbourne          | SGL     | ✓✓✓✓✓chedules                 |    |    |    |    |           |    |    |    |    |     |    |     |
| Austria                              |         |                                   |    |    |    |    |           |    |    |    |    |     |    |     |
| CYBERGRID GMBH                       | cyberLAB| ✓✓✓✓✓chedules                 |    |    |    |    |           |    |    |    |    |     |    |     |
| AIT Austrian Institute of Technology| SmartEST| ✓✓✓✓✓chedules                 |    |    |    |    |           |    |    |    |    |     |    |     |
| Belgium                              |         |                                   |    |    |    |    |           |    |    |    |    |     |    |     |
| IMEC                                 | PV Department | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| VITO                                 | EnergyVille | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| Brazil                               |         |                                   |    |    |    |    |           |    |    |    |    |     |    |     |
| University of São Paulo              | NAPREI  | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| University of Campinas               | LabREI  | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| Canada                               |         |                                   |    |    |    |    |           |    |    |    |    |     |    |     |
| Ryerson University                   | SESG Lab| ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| University of Ontario                | ERC     | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| Kinectrics Inc                       | GRIDSIM | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| Polytechnique Montreal               | OSG     | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| Cyprus                               |         |                                   |    |    |    |    |           |    |    |    |    |     |    |     |
| University of Cyprus                 | FOSS    | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| Denmark                              |         |                                   |    |    |    |    |           |    |    |    |    |     |    |     |
| Aalborg University                   | SES Lab | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| Finland                              |         |                                   |    |    |    |    |           |    |    |    |    |     |    |     |
| VTT Ltd                              | MP-Espoo| ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| France                               |         |                                   |    |    |    |    |           |    |    |    |    |     |    |     |
| University of Lille                  | L2EP    | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| CNRS                                 | PROMES  | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| Electrical Engineering Laboratory    | PREDIS  | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| EDF                                  | Concept Grid | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| Germany                              |         |                                   |    |    |    |    |           |    |    |    |    |     |    |     |
| TU Dortmund                          | SGTL    | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| RWTH Aachen                          | ACS     | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| TU Berlin                            | SENSE   | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| Greece                               |         |                                   |    |    |    |    |           |    |    |    |    |     |    |     |
| National Technical University of Athens| EES-lab | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| CRES                                 | Microgrid and DER Lab | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |
| Ireland                              |         |                                   |    |    |    |    |           |    |    |    |    |     |    |     |
| University College Dublin            | IE Lab  | ✓✓✓✓✓ |    |    |    |    |           |    |    |    |    |     |    |     |

Continues
### TABLE 2  Continued

| Institute/Company                  | Lab Acronym          | Categories of Smart Grid Research |
|------------------------------------|----------------------|-----------------------------------|
| **Italy**                          |                      | **DA**  | **GM**  | **ES**  | **MA**  | **Gen & DER** | **EM** | **SH** | **SC** | **DR** | **ICT** | **CS** | **AMI** |
| ABB Ltd                            | Smart Lab            | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| Joint Research Centre              | SGI Lab              | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| Joint Research Centre              | EPIC                 | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| Joint Research Centre              | VeLA8                | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| Joint Research Centre              | VeLA9                | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| Ricerca sul Sistema Energetico SpA | RSE DER-TF           | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| University of Pisa                 | SGL                  | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| Politecnico di Bari                | MG-Lab PrInCE        | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| Latvia                             |                      |         |         |         |         |           |       |       |       |       |         |       |         |
| Institute of Physical Energetics   | SGRC                 | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| (IFE)                              |                      |         |         |         |         |           |       |       |       |       |         |       |         |
| **The Netherlands**                |                      |         |         |         |         |           |       |       |       |       |         |       |         |
| TU Delft                           | ESP Lab              | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| DNV GL                             | FPGL                 | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| Joint Research Centre              | SG Home Lab          | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| **New Zealand**                    |                      |         |         |         |         |           |       |       |       |       |         |       |         |
| University of Auckland             | PSG                  | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| **Norway**                         |                      |         |         |         |         |           |       |       |       |       |         |       |         |
| Norwegian University of Science    | NSGL                 | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| and Technology                     |                      |         |         |         |         |           |       |       |       |       |         |       |         |
| **Poland**                         |                      |         |         |         |         |           |       |       |       |       |         |       |         |
| Wroclaw University of Technology   | PLC Lab              | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| Lodz University of Technology      | DGLab                | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| **Portugal**                       |                      |         |         |         |         |           |       |       |       |       |         |       |         |
| EDP SA                             | EDP Labelec          | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| R&D Nester                         | R&D Nester Lab       | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| Universidade do Minho              | GEPE                 | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| **Portugal**                       |                      |         |         |         |         |           |       |       |       |       |         |       |         |
| INESC TEC                          | SG & EV Lab          | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| National Laboratory for Energy and | LNEG                 | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |
| Geology                            |                      |         |         |         |         |           |       |       |       |       |         |       |         |
| **Russia**                         |                      |         |         |         |         |           |       |       |       |       |         |       |         |
| Skoltech                           | Smartgrids Lab       | ✓       | ✓       | ✓       | ✓       | ✓         | ✓     | ✓     | ✓     | ✓     | ✓       | ✓     | ✓       |

Continues
### TABLE 2  Continued

| Institute/Company | Lab Acronym | Categories of Smart Grid Research | DA | GM | ES | MA | Gen & DER | EM | SH | SC | DR | ICT | CS | AMI |
|-------------------|-------------|-----------------------------------|----|----|----|----|-----------|----|----|----|----|-----|----|------|
| Spain             |             |                                   |    |    |    |    |           |    |    |    |    |     |    |      |
| Instituto Tecnológico de la Energía | ITE | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| IMDEA             |             |                                   | ✓  | ✓  | ✓  | ✓  | ✓         | ✓  | ✓  | ✓  | ✓  | ✓    | ✓  | ✓    |
| CENER             |             |                                   | ✓  | ✓  | ✓  | ✓  | ✓         | ✓  | ✓  | ✓  | ✓  | ✓    | ✓  | ✓    |
| Tecnalia          |             |                                   | ✓  | ✓  | ✓  | ✓  | ✓         | ✓  | ✓  | ✓  | ✓  | ✓    | ✓  | ✓    |
| CIRCE             |             |                                   | ✓  | ✓  | ✓  | ✓  | ✓         | ✓  | ✓  | ✓  | ✓  | ✓    | ✓  | ✓    |
| DNV GL Spain SL   |             |                                   | ✓  | ✓  | ✓  | ✓  | ✓         | ✓  | ✓  | ✓  | ✓  | ✓    | ✓  | ✓    |
| Universidad Politécnica de Madrid | MagicBox | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| UFD SA            |             |                                   | ✓  | ✓  | ✓  | ✓  | ✓         | ✓  | ✓  | ✓  | ✓  | ✓    | ✓  | ✓    |
| Ormazabal Corp    |             |                                   | ✓  | ✓  | ✓  | ✓  | ✓         | ✓  | ✓  | ✓  | ✓  | ✓    | ✓  | ✓    |
| ceit-IK4          | iSare       | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| UPC-BarcelonaTech | CITCEA Lab  | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Sweden            | STRI AB      | STRI RD&D                         | ✓  | ✓  | ✓  | ✓  | ✓         | ✓  | ✓  | ✓  | ✓  | ✓    | ✓  | ✓    |
| Switzerland       | École Polytechnique Fédérale de Lausanne | DESL | ✓  | ✓  | ✓  | ✓  | ✓         | ✓  | ✓  | ✓  | ✓  | ✓    | ✓  | ✓    |
| UK                | Durham University | SGLab | ✓  | ✓  | ✓  | ✓  | ✓         | ✓  | ✓  | ✓  | ✓  | ✓    | ✓  | ✓    |
| Imperial College of London | SELab | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| University of Strathclyde | PNDC | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Newcastle University | SGLab | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| USA               | NC State University | FREEDM | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| EnerNex Corp      | SGL          | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Princeton University | PENSA | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Florida State University | CAPS | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Lawrence Berkeley National Laboratory | FLEXLAB | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| UC Irvine          | APEP         | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Kansas State University | SGLab | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| NREL              | ESIF         | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Colorado State University | APEL | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Colorado School of Mines | ACEPS | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| MSL               | Smart Grid Center | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Washington State University | SGDRIL | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

*Note.* Indicated are the categories of research, in which they are active. The categories are distribution automation (DA), grid management (GM), energy storage (ES), market (MA), generation and distributed energy resources (Gen & DER), electromobility (EM), smart homes (SH), smart cities (SC), demand response (DR), information and communication technologies (ICT), cybersecurity (CS), and advanced metering infrastructure (AMI).*
A quite strong connection is noticed between the categories
- EM and storage, where 42 labs carry out research on both categories; and
- EM and GM, with 36 labs working on both categories.

A less strong connection but still some is noticed between the categories
- DA and GM: Thirty-seven labs carry out research on both categories, but there are 20 labs that work on GM without activities on DA; and
- SH and SC: Twenty-eight labs work on both categories, but 16 labs work on SH subjects without focusing on smart city issues.

A weak connection or very weak connection is noticed between the categories
- Market and DR: Whereas 33 labs work on both subjects, DR is carried out by 24 labs, where market is not one of their core activities;
- AMI and SH: There are 23 labs performing research on both topics; however, 22 labs focus on SH without having AMI as one of their main activities; and
- AMI and DR: There are 27 labs that carry out research on both categories and other 27 labs that work on DR without focusing on AMI, as core activity.

The strong connection between GM and Gen & DER is justified by the fact that managing energy from DER requires good GM techniques. In addition, storage can contribute in managing energy from DER, which explains their strong connection. Electric vehicles can result in a potentially available storage unit, whereas the increase in the number of electric vehicles requires an enhanced management of the grid. These issues explain the connection between EM and storage and between GM and storage. Furthermore, AMI can involve ICT communication issues; therefore, there is a strong connection between these categories. On the other hand, SH may be an element of the SC, but it is observed that focus on SH issues does not necessarily mean that the lab works also on SC.
Both SH and DR topics can be connected to AMI issues; however, these categories can cover a wide span of sub-topics, and it is likely that AMI is not related to such activities. It is also observed that there is a weak connection between market and DR categories, which may indicate the need to link the two categories better, since DR can be seen as a market product and offered to market participants.

Furthermore, we are using the below Venn diagrams to show the dependencies among more than two categories of research activities in the labs. At first, in Figure 6, we choose to examine the dependencies among the five most popular activities, ie, Gen & DER (in 91% of the labs), GM (76%), DR (76%), ES (75%), and SH (60%).

From Figure 6, we can see that the majority of these labs performs activities in all five categories at the same time.
time, and almost all the rest perform activities in at least two categories. Only three of these labs perform activities solely on DER, GM, and DR, something which along with Figure 4 show the interdisciplinary nature of most of the labs. In the next Venn diagrams, we focus on groups of three activities.

Figure 7 shows the dependencies among DER, GM, and DR activities, which are the three activities with the highest number of labs working on them, more than 75%. From Figure 7, we can see that DER is basically the connecting activity among the three; i.e., most of the labs work on all three categories, and there are also many labs working on DER and GM or DER and DR, but only four do not work on DER. This might be explained by the fact that DR is an application or a service that can be used for GM, but in most cases, it is investigated in combination with DER.

Figure 8, on the other hand, presents the dependencies among the three of the least popular activities, i.e., AMI (47%), market (48%), and CS (45%). Here, we can see that, in contrast to Figure 7, most of these labs (24) work only in one of these activities, fewer in two activities (18), and the minority (15) works in all three. AMI seems to be the most dependent category, since it refers to the underlying technology, while market is the activity with the fewer dependencies. One could say that these less prevalent categories are secondary activities, which are mostly investigated in combination with some of the more prevalent topics.

Another important aspect is to identify for which kind of organizations the smart grid labs are conducting their research. Most of the labs are doing their work for more than one entity, which is probably related to the fact that most of the labs also perform many research activities at the same time. Figure 9 presents a bar diagram, where for each of the reported research activities, the percentage of the labs that conducts research for a specific entity is shown.

It appears that for all categories of research activity, around 80% of the labs conduct research for some utility, where by the term utility, we refer collectively to DSOs, TSOs, electricity suppliers, generation companies, etc. Most prominently, 83% of the labs working on AMI...
conduct their research for some utility. The second most preferred partner is industry, especially in the activities of SC, SH, EM, DA, and ICT with 70% of the labs in each category conducting research for industrial partners. Academia is also a very important partner for the labs and for some activities even more than industry. In particular, for labs working on GM, Gen & DER, and DR, more labs conduct their research for universities than for industry. However, this is not necessarily indicative of the research field itself, since it could be a sign either that the industry is mature and works independently in that field (eg, for GM and Gen & DER) or that the field is still emerging, and therefore, the research is mainly done in academia (eg, for DR). Government comes after, with 50% to 60% of the labs conducting research for it, while other research organizations are the target of only 30% to 40% of the labs. There are also a few other types of entities, for which the labs are conducting their research. However, these are not quite significant, except perhaps the fact that 8.5% of the labs that have market-related research activities report some other type of entity, showing the different nature of this topic, in comparison with the rest that are more technical.

4.3 Institutes’ publications and collaborations

In the following, we present results from an analysis performed on data regarding the publications of the 75 laboratories including peer-reviewed papers in scientific journals, books, and conference proceedings. The data have been collected using the scientific publication search engine Scopus. A keyword search has been performed scanning all documents’ titles, abstracts, and key words for smart grid(s). In addition, the search had been limited to affiliations with the respective institutes included in this review paper. It needs to be noted that the affiliation with the individual laboratories is often not specified in the details of a publications and it was thus decided to conduct this publication search extending it to the institutes the laboratories are affiliated with. The gathered publications have been sorted by topic according to the categories defined in Section 2 and aggregated for all the institutes. The evolution of scientific publications by the listed institutes between 2008 and 2018 by category is displayed in Figures 10 to 12.

Overall, one can observe an increase in the number of publications over the years in virtually all categories, underlining the growing interest in smart grids by the scientific community. There is also a plateauing or even plunging in the number of publications in 2013 and 2014, which can be associated with the ending of the 7th Framework Programme for Research and Technological Development (FP) of the European Commission in 2013, a large funding scheme for research and innovation projects, and the launching of the 8th FP commonly known under the name Horizon 2020, which started in 2014.

Most noteworthy is the predominance of publications on the topic of EM, also given the fact that it is not the category, which most laboratories are active in (see Table 3). However, there are some laboratories solely focusing on EM and thus publishing only papers on this particular topic, and it is also true that there are several synergies between EM and other topics. Conversely, it is also interesting to consider the evolution of one of the least investigated research areas, namely, CS. There is a plunging in the number of publications to be observed in recent years. Especially, in the context of current trends in digitalization, also to be observed in the large number of publications on ICT matters, data and cybersecurity become an ever more important issue, and an increased interest in research also in the context of smart grid research would be desirable.
Additionally, an analysis of the affiliations between the listed institutes on smart grid publications has been performed, in order to examine the collaborations between the smart grid labs. In Figure 13, the results of this analysis are displayed. The 15 institutes that appear to have the highest number of publications have been chosen to be displayed. It needs to be noted that as before, it was not possible to restrict the publications and thus, affiliations search to only the specific smart grid laboratories, as the turnout of results would have been underrepresentative. On the contrary, it is likely that the representation gives an overestimated view of the number of publications of a certain lab; therefore, the results of the institutes with which the labs are associated are shown. The scope is to give a generic trend regarding collaborations, rather than the exact number of collaborations between the smart grid labs, since this can be hardly recognized by publicly available data.

Concretely, we find that between 2008 and 2018, Aalborg University, AIT, TU Delft, INESC TEC, and RWTH Aachen have produced the most scientific publications on smart grids. Furthermore, already only between the 15 institutes displayed in Figure 13, we find that there are numerous collaborations, which is a desirable trend. It can create synergies between the different institutes and research topics and help advance the research on smart grids effectively. However, there is room for more affiliations, and this work is expected to facilitate collaboration between institutes through showing the different focus areas of the laboratories and institutes and thereby help identify possible cooperation. It needs to be noted that only the collaborations between these 15 institutes are shown but each institute might have further collaborations with the other institutes. It is thus not the case that the remaining publications have been published without any collaboration.

4.4 Broader challenges linked to smart grid research

In this section, we briefly discuss challenges linked to the research on smart grids by considering the bigger picture and putting research efforts in this field into context.

There are a lot of challenges when it comes to the modernization and digitalization of the electricity grid. One of the major ones is the environmental challenge, which calls for the integration of more renewable generation in the system. The intermittency of renewables adds additional defiance to their introduction to the grid, as this can add problems as imbalances to the system. The RES introduction effort calls for intensive research from an early stage, which is conducted in the various laboratories. Thus, it is not a surprise that Gen & DER is one of the major research topic of the surveyed labs. Furthermore, large capacities of RES require also energy storage and grid management, and these are again main topics defined by the research laboratories. The development and employment of innovative technologies are another challenge that the grid is facing toward its transition to smart grids, which includes SH, DA, EM, AMI, and ICT systems. Introducing innovative technologies to a system that works many years under legacy components is an issue that requires intense research on the innovative technologies and the
specific requirements to adopt them to the system. Additionally, changing and modernizing the whole scenery of the energy system automatically create new business and market needs. End users have the opportunity of becoming active players as new products and technologies as DR appear in the energy market. Thus, topics as markets and DR appear high in the interest of research laboratories.

The transition of the energy system as a whole is one of the most challenging tasks of our time that requires joint efforts of research, politics, and industry and at the same time has the potential to create various new opportunities to creating a system that is more sustainable and efficient and that engages all stakeholders more effectively.

5 | CONCLUSION

This paper provides an overview of the current research activities performed by 75 smart grid laboratories identified worldwide. In this time of major challenges and changes ahead of us, it is vital to join efforts to advance the transition from the traditional electricity grid to a smart grid. Facilitating cooperation between institutes is even more important in a field that is aiming to reach more interconnectivity and integration of the energy networks as smart grid research.

The areas of research were identified for the 75 labs included in this work, and interactions between different activities were recognized and discussed. A brief summary of the labs aids the reader to grasp an overview of the specific research conducted in each laboratory.

The majority of labs gathered in the context of this survey is located in Europe with 58 of the total 75. In terms of research activities, the labs are often active in a multitude of categories, while there are also a couple of laboratories focused on specific topics, such as EM. The most commonly studied category within smart grid research is Gen & DER with 68 labs or 91% of all considered labs. We also find that there are a number of research category combinations that are particularly often found to be in the focus of the labs’ research. GM and Gen & DER are categories studied simultaneously by 55 labs; the same applies for Gen & DER and ES. Weak connections are found between the categories of AMI and SH and between AMI and DR, denoting a potential to increase the research efforts to advance the knowledge in the overlapping areas of research in these categories. We furthermore found that the labs most commonly conduct research for utilities and the industrial sector in general, while also academia and government show large interest in the research of the smart grid labs.

The trend of increasing research in the area of smart grids is very promising and gives rise to expectations of major advances in the upcoming years.

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