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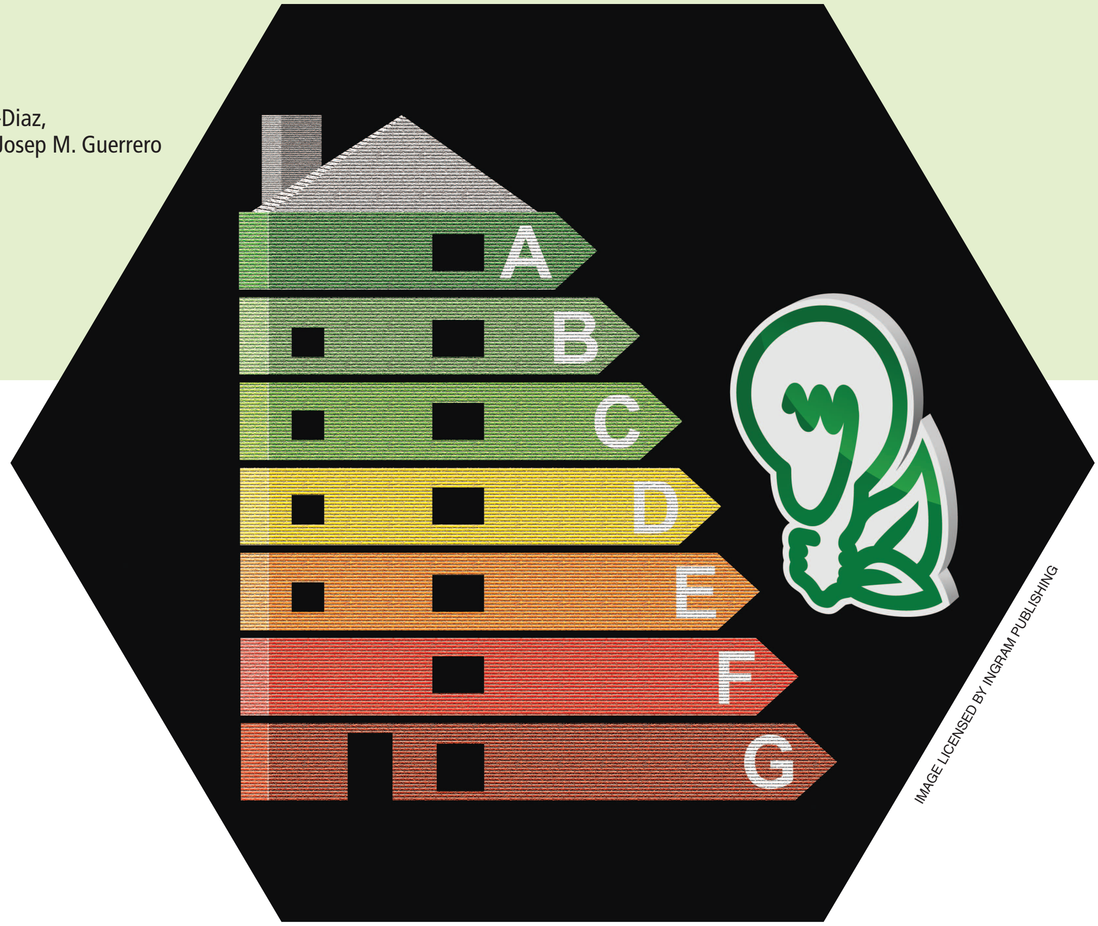

Intelligent DC Homes in Future Sustainable Energy Systems

When efficiency and intelligence work together.

THE EVIDENCE THAT CLIMATE CHANGE IS REAL AND MOST likely caused by human-related activities has made the international community consider a new energy model. Europe has led the initiative, moving away from fossil fuels toward renewable energies, while powerful countries such as the United States and China are lagging behind and still rely heavily on coal, gas, and oil as energy sources. Europe has set ambitious goals for 2020

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regarding the increase of renewable energy production, energy efficiency, and greenhouse gas emission reduction. The concept of a microgrid is perfectly aligned with the new energy strategy. A microgrid eases the integration of renewable energy sources (RESs) and energy-storage systems (ESSs) at the consumption level, aiming to increase power quality, reliability, and efficiency. The increasing importance of dc-based loads has reopened the discussion of dc versus ac distribution systems. As a consequence, much research has been done on dc distribution systems and their potential for residential applications. Furthermore, the growing presence and use of smart devices in homes reveal a promising future for intelligent homes integrated in the Internet of Things (IoT), where residential electrical power systems work in cooperation with smart devices to achieve smarter, more sustainable, and cleaner energy systems.

A NEW ENERGY MODEL

First-world countries have been developing new energy policies to stop or reduce climate change and its dramatic global consequences. The new energy policies target the reduction of fossil fuel use, increase of energy efficiency, and integration of renewable sources to reduce pollution and greenhouse gas emissions, reduce dependency on imported energy sources, and achieve a cleaner and sustainable energy system.

The European Commission has set the Renewable Energy Directive, which establishes a common policy for the countries in the European Union (EU) for the promotion of RESs (Figure 1). The main goals are to achieve a 20% reduction in greenhouse gas emissions, 20% renewable energy consumption, and a 20% reduction in energy consumption by 2020 (compared to the levels in 1990). The plan includes the electricity, heating and cooling, and transport sectors. Each participating country has different goals for increasing the share of renewables in their energy consumption, ranging from 49% for Sweden to 10% for Malta. The EU countries have adopted national renewable energy action plans to show they will meet their respective goals. Denmark has set some of the most ambitious goals, and its government intends its energy sources to become 100% renewable by 2050, including the energy used for both electricity production and the transportation sector.

So far, the efforts of EU countries have been concentrated on installing wind and photovoltaic (PV) power plants, with comparatively little done to improve system efficiency and reduce energy consumption. The actions already taken and the plans developed to fulfil the targets by 2020 are not enough to tackle the issue that initially prompted the EU to set new energy policies—climate change. Therefore, considering the long-term objective of a clean and sustainable energy system, the way we handle energy is as important as from where it comes.

For instance, what if, instead of focusing the effort on how we can supply the global energy demand with more renewable energy generation, we investigate how consumers can supply their own energy and optimize energy consumption by becoming self-sustainable? Currently, actions are being taken at a large-scale level; however, instead of considering entire countries at once, we should go deeper and promote local energy production, region by region, town by town, building by building, or even household by household when it is feasible. Aside from the already studied benefits of moving production sites closer to points of consumption, an important and not yet considered strategy is to familiarize the population with renewable energy technologies and self-sustainability.

Regarding energy optimization at the residential level, the future yields to the concept of the IoT. All devices in the home will be able to interact with each other and their users to emphasize optimized energy consumption. The idea

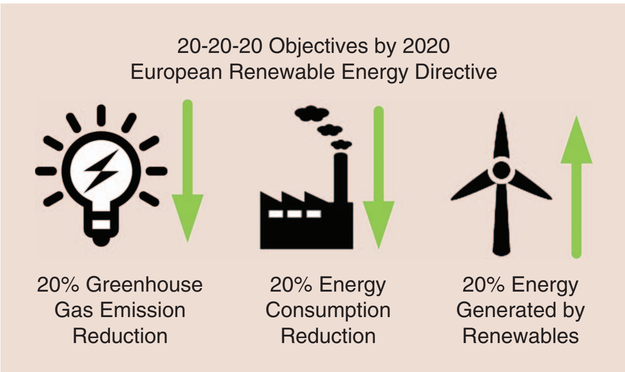

FIGURE 1. The EU energy policy's goals for 2020.

> The energy policies target the reduction of fossil fuel use, increase of energy efficiency, and integration of renewable sources.

behind the IoT for home automation is that every device will be able to communicate with and provide information to the consumer or energy-management system (EMS). By collecting and monitoring consumption patterns, it is easier to adjust the electricity demand and generation, especially when using RESs such as PV and wind. Consumers will be aware of their consumption, and, therefore, they can adjust their behavior accordingly. A significant reduction in consumption can be achieved when the user is aware of the cost of the energy that is being consumed [1]. Furthermore, the EMS can reduce energy waste resulting from users' bad habits, e.g., by turning off lights in unoccupied areas of the house or scheduling the heating/cooling system so it is not on when the house is empty. The EMS would be able to decide the best time to run certain appliances, such as dishwashers and washing machines, depending on the price or availability of energy.

To achieve a sustainable energy system, the focus should not be limited to energy generation. The distribution of the energy needs to be done efficiently, and the waste of energy should be minimized.

DC AS A TECHNOLOGY FOR FUTURE ELECTRICAL POWER SYSTEMS

An efficient distribution system is a key factor for sustainable energy systems. Today, there is an open discussion on whether to use ac or dc electrical power systems. This matter can be traced back to the battle between Edison and Tesla/Westinghouse more than a century ago [2]. The technology available back then made the ac option far more advantageous; consequently, electrical power systems worldwide are ac based. Today's scenario is different, and dc-based power systems offer interesting advantages in terms of simplicity, cost, and efficiency [3].

DC technologies have been widely used in several applications and industries, such as automotive, aerospace, telecom, or electricity transmission. In the automotive industry, 12-Vdc distribution systems are used to distribute energy and supply the electric/electronics equipment in the vehicles; in telecom applications, 48-Vdc distribution systems are widely used; and, for long-distance or undersea electricity transmission, high-voltage dc systems offer significant advantages over high-voltage ac. Furthermore, satellites have been using dc distribution systems for quite a long time, since the only source of energy available in space comes from PV panels, which are dc-based energy generators.

So, what has changed that makes dc distribution systems a stronger candidate for low-voltage distribution? There are several considerations that influence whether an ac or dc system is more advantageous, and today's scenario tips the scale toward a future dc distribution system. The following are the main factors that support the use of dc systems:

- *DC generation and storage:* Suitable renewable energy generators, such as PV panels and fuel cells (FCs), and ESSs, such as batteries, are dc based.

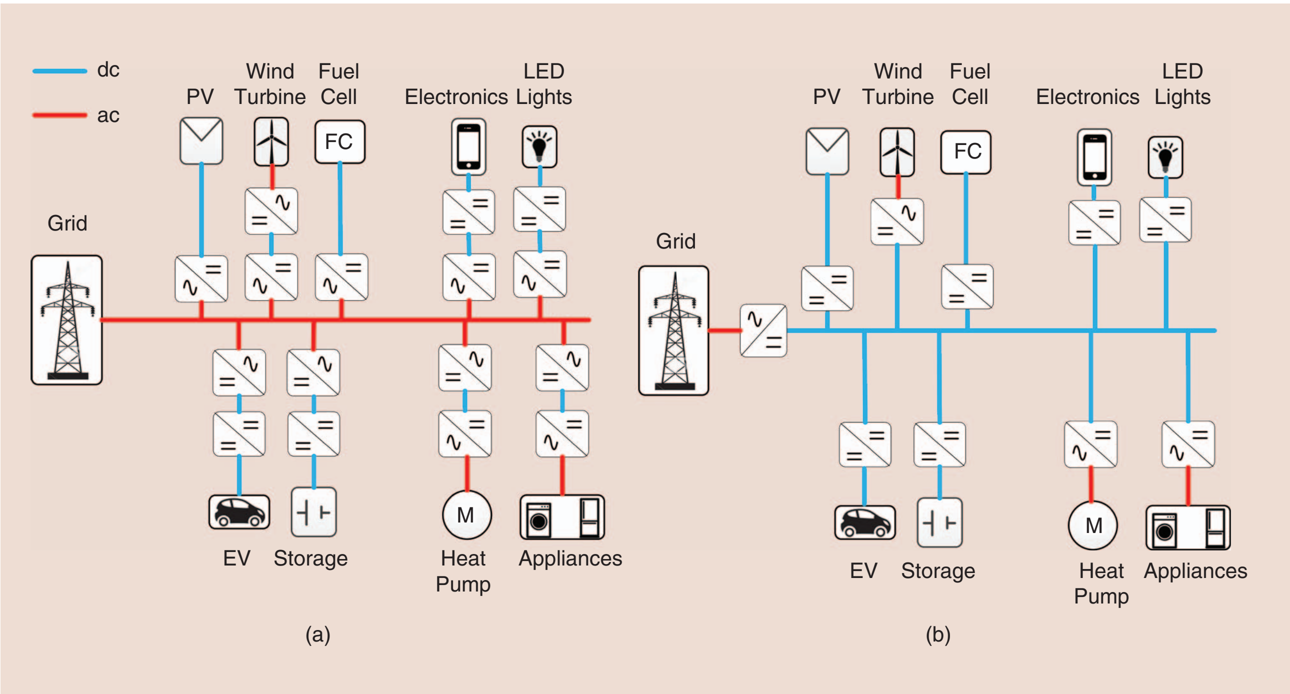

FIGURE 2. Conversion stages are reduced when switching from (a) ac to (b) dc distribution systems for residential applications.

- *DC loads:* The presence and consumption of dc loads is constantly increasing because of the growing numbers of electronic devices in buildings and homes.
- *Electric vehicles (EVs):* The future integration of the electric vehicle in the power system will increase the consumption of dc devices (batteries) in buildings or homes.
- *Efficiency:* DC distribution systems are intrinsically more efficient than their ac counterparts, since, in dc, there is no skin effect in the conductors or reactive power loading the lines.
- *Conversion stage reduction:* Interconnecting and distributing the energy among mostly dc-based agents (sources, loads, and storage) through a dc power system avoids unnecessary dc–ac and ac–dc conversions, which are a waste of energy.

Figure 2 gives a clearer picture of the aforementioned aspects, showing the reduction of the conversion stages in the load power converters, storage systems, and sources, when switching from ac to dc distribution systems in residential applications. Something that is not straightforwardly appreciated is that, when the energy consumed by the load comes from the RESs, the conversion stages are reduced; however, in real applications, the generation may not always meet the consumption. Therefore, energy is often stored in an ESS before consumption, which only increases the potential energy savings implementing dc technologies.

Recently, dc distribution systems have made their way into electrical power systems for industrial applications, especially in the telecommunication industry. In data centers, low-voltage dc (LVdc) architectures have been widely studied [4], [5], and several facilities are currently using LVdc distribution systems. Data centers demand highly reliable systems, where the integration of uninterruptible power systems is a priority. The installation of dc distribution systems reduces the conversion stages significantly, making the system more efficient.

In data centers, the enhancement of energy efficiency comes with an extra advantage. Cooling systems are a large part of the overall energy consumption, and by increasing overall efficiency, the losses are reduced, and, therefore, the amount of heat that needs to be evacuated is smaller, leading to an extra reduction of the energy consumption by the cooling system.

Introducing dc distribution systems for widespread industrial and residential applications seems like the next reasonable step, since several industries already benefit from the advantages. Brian T. Patterson, founder of Emerge Alliance (EA), has also shown the importance of dc technology in a future electrical grid "enernet" and zero-net-energy buildings [6].

There are a few questions that still need to be answered to see the true potential of dc distributions systems for residential applications. AC distribution systems have recently been losing ground against dc; however, when looking at residential applications, dc systems still have a long road ahead. The lack of regulation and standardization and the development of protections are probably the main challenges that dc power systems need to overcome before being considered a suitable option to replace ac power systems.

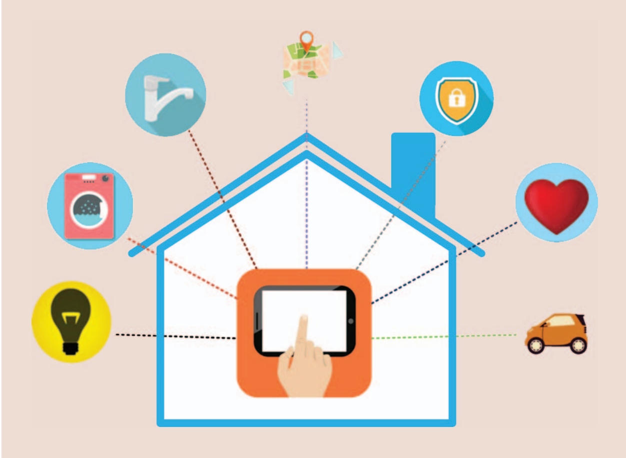

FIGURE 3. The IoT concept for residential applications.

THE IoT IN MORE SUSTAINABLE AND EFFICIENT HOMES

The Renewable Energy Directive set a goal of 20% reduction of energy consumption by means of energy efficiency improvements. As explained previously, overall system efficiency can be easily enhanced by taking the generation closer to the consumption and adopting dc technologies for energy distribution. However, the energy consumption can be further cut by reducing the energy wasted due to people's bad habits.

The application of the IoT concept could bring significant energy savings. This is currently a hot topic, and it can also be applied at large scales—it is not only for home automation. For instance, when a city applies the IoT concept, both its administration and citizens benefit. The lower operating costs would bring an economic advantage for the city, and the citizens would see enhancements of the quality of the services provided. Many sectors and services would benefit

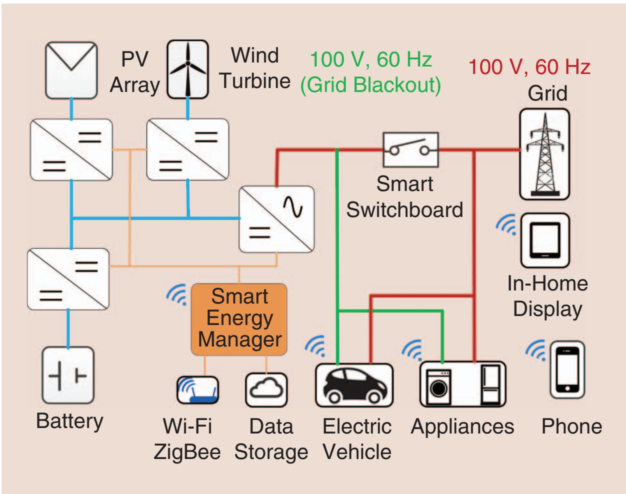

FIGURE 4. The Fukuoka Smart House.

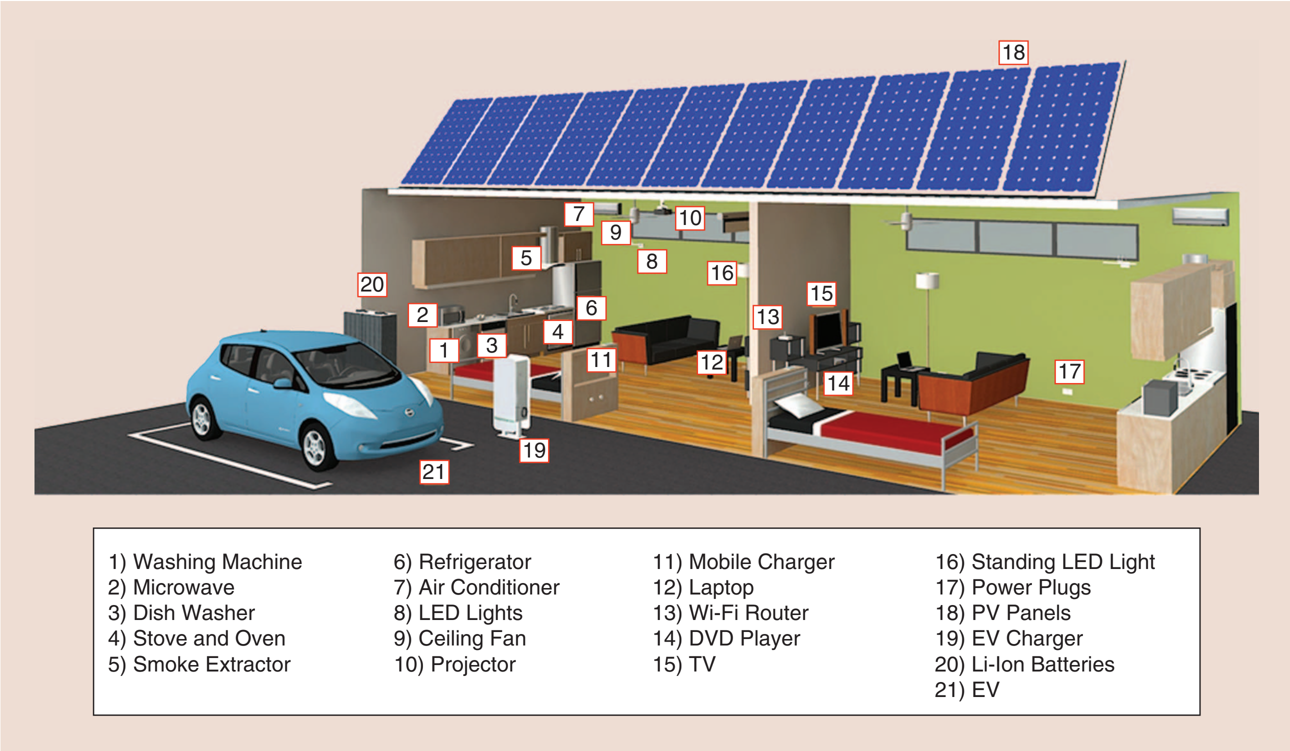

FIGURE 5. The intelligent dc home at Aalborg University.

The lack of regulation and standardization and the development of protections are probably the main challenges that dc power systems need to overcome before being considered a suitable option to replace ac power systems.

from the IoT, e.g., through the improvement of waste management; air-quality enhancement; noise emission, traffic congestion, and energy consumption reduction; parking availability information; and landmarks structural conservation improvement [7]. The "Padova Smart City" project seeks the experimental implementation of the IoT concept applied in an urban environment [8].

Going back to residential applications, the IoT at home can be implemented by connecting several smart devices to a central EMS with decision-making capabilities (Figure 3). Once we start to interact with the devices in our daily routine, the EMS can detect our presence, learn our habits, and act accordingly to optimize the energy consumed in the home. The learning process can cover a vast number of variables, such as

- the position of the people in the house
- the time we leave or get home
- when we cook, clean, or sleep
- how long we shower
- how hot we like the water when taking a shower.

But how can the EMS save energy by studying our habits? It can correct bad habits, such as leaving the lights on in empty rooms, disconnect the heating system if there are windows or doors open, and schedule the start-up of the dishwasher or washing machine based on the price of the electricity, or the availability of energy if there is a local RES installed in the home.

These features might sound futuristic, but there are already commercially available products, such as smart switches, plugs, LED lightbulbs, and all kinds of sensors, cameras, and actuators, that allow you to remotely enable and disable appliances or the heating and cooling system, check energy consumption, or command your TV to record your favorite TV show.

CHALLENGES AND BARRIERS FOR INTELLIGENT DC HOMES

There are several of technical and social challenges that these technologies need to face before entering the mass market; however, the lack of standardization and codes for both dc and the IoT is the main issue when trying to implement such systems.

As mentioned previously, the IoT concept intends to create a global network for the interconnection of future everyday smart devices, from a dishwasher in a home to a parking sensor in a city, aiming to improve the automation in all fields, bringing opportunities and benefits to people, companies, and administrations. However, the integration of many heterogeneous fields in the same system is not easy, and several challenges need to be overcome before implementation.

- *Connectivity:* There are quite a few communication standards being used in today's devices, e.g., Bluetooth, Wi-Fi, ZigBee, and PLAN. For the seamless integration of every device, new open-source communication protocols are needed.
- *Consumption:* Power is critical for these applications since most of the devices run on batteries and it is expected that they will be in use for years. The solution might be to use harvested-power devices, which generate the energy from vibrations, light, or heat.
- *Security:* This is more of a social issue than a technical one. People are usually reluctant to share their information, and this goes against the principles of the IoT, since information is vital. Nevertheless, the devices need to incorporate built-in hardware security technologies so unauthorized access to personal information is prevented.
- *Lack of infrastructure:* Developers and companies need a common infrastructure formed by software and hardware to reduce development costs and boost the creation of IoT-compatible devices.

In addition, there are particular considerations associated with the implementation of dc distribution systems in residential applications.

- *Lack of standards and codes*: Several organizations, such as EA, the European Telecommunications Standards Institute, the International Electrotechnical Commission, and the IEEE, are already actively developing the necessary regulations and standards.
- *Safety and protection:* These issues derive from the use of dc because ac protections used zero crossing of the currents to interrupt it. Furthermore, the installation of RESs and ESSs makes the power flow bidirectional through the lines; hence, new schemes are required to detect and isolate faults and the section affected without disconnecting the whole system.
- *Lack of commercial products*: When analyzing dc systems in residential applications, it is easy to notice that there are few commercial products ready to be used with dc voltage. For instance, in dc appliances/devices, small modifications are required to make them "dc-ready."

PROTOTYPES OF DC HOMES

Generally speaking, there are not many existing facilities, buildings, or homes running on dc voltage; the supremacy of ac is complete. However, because of the interest and potential advantages, dc systems are becoming a focus of research efforts, and the first prototypes are being implemented.

Japan is one of the leading countries regarding dc distributions systems for residential applications. Since the 2011 earthquake and tsunami that left most of the country with cuts in the electricity supply, the Japanese agenda has shifted toward energy-independent or sustainable-energy homes. For instance, in Tohoku Fukusi University in Sendai City, a microgrid was implemented, and it has been running since 2008 [9]. The microgrid has several local generation sources, gas engines and PV arrays, and ESSs formed by phosphoric acid fuel cells. The facility, in particular, and the technology, in general, attracted the attention of the Japanese government because the microgrid kept working autonomously from the grid during the earthquake in the

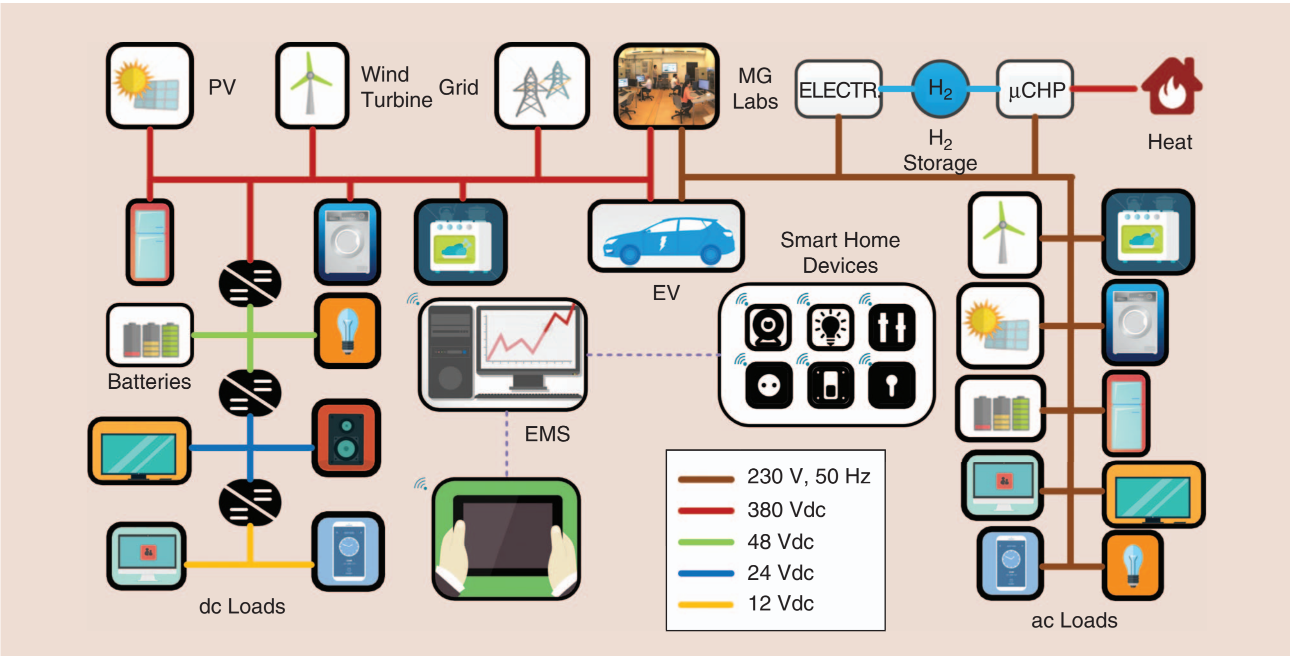

FIGURE 6. The power architecture of the intelligent dc home at Aalborg University. CHP: combined heat and power.

Tohoku area in 2011, while the main grid was down for three days.

A demonstration facility has been built in Island City in Fukuoka City, Japan. The power architecture of the house is shown in Figure 4. It consists of a hybrid ac–dc distribution system, RESs, an EMS, and loads. The ac system, which is fed from an inverter connected to a common dc bus, is only used to supply power to the appliances in the house. The common dc bus is running at 380 Vdc, which interconnects the renewable generation and the ESSs.

Taiwan has also bet on dc for more efficient distribution systems; in consequence, a demonstration facility has been built by the Elegant Power Application Research Center. The system is formed by energy generators (PV panels, a wind turbine, and a fuel cell), energy-storage devices (a Li-ion battery and flywheel), dc loads (appliances and equipment), a monitor and control center, and an interconnection with the main grid [10].

Europe is lagging behind the Asian countries, especially Japan, regarding implementation of dc distribution systems for residential applications. At Aalborg University, Denmark, an intelligent dc home is being implemented (Figures 5 and 6). The Danish Council for Strategic Research on Sustainable Energy Environment has granted funding for the project to develop a pioneer facility in Europe, which presumably will boost the research and the involvement of companies and industry for the development of dc technologies for residential applications [11].

The facility is intended to serve as a test bed for appliances, dc–dc converters, management algorithms, and communications systems as well as to investigate the energy saving potential, benefits, and barriers for directly using electricity in dc form from energy generated on site, rather than converting it to ac for distribution. In other words, the systems shown in Figure 2 are going to be implemented and studied. The intelligent dc home will be divided into two different sections, both with fully functional appliances: electronics that are typically used at home and smart home devices. A central EMS controls the energy flow within the facility, seeking the optimization of the energy consumption.

CONCLUSION

It is clear that, in the near future, sustainable and renewable energy systems will be a must; otherwise, global warming and climate-change-derived effects will have catastrophic consequences for all nations worldwide. There is no doubt that the energy production system needs to be changed, since it relies on oil, gas, and coal for energy generation; however, rather than focusing only on supplying the energy demand with new sources, reducing the demand should also be explored as it would bring similar benefits. The implementation of the dc technologies for efficient energy distribution, together with intelligent platforms for optimizing resources and reducing wasted energy, is the goal that we all need to work toward.

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