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Intelligent DC Homes in Future Sustainable Energy Systems
When efficiency and Intelligence Work Together

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***Abstract*—The evidences that climate change is real, and the fact that it is most likely caused by human-related activities, has made the international community to considered a new energy model. Europe has led the initiative of moving away from fossil fuels to renewable energies, where other powerful countries, as USA and China, are lagging behind, and still highly rely on coal, gas and oil as a source of energy. Europe has set ambitious goals for 2020 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 easy the integration of renewable energy sources and energy storage systems at the consumption level, aiming to increase power quality, reliability and efficiency. On top of this, the increasing of DC-based loads has re-opened the discussion of DC vs AC distribution systems. As a consequence a lot of research has been done on DC distribution systems and its potential for residential applications. Furthermore, the increasing presence and used of smart devices in homes, reveal a promising future for intelligent homes, integrated in the Internet of Things concept, where the residential electrical power systems works in co-operation with the smart devices, in order to achieve a smarter, more sustainable, and cleaner energy systems.**

I. A New Energy Model

First-world countries have been developing new energy policies in order to stop or reduce the climate change, and its dramatic consequences the global population. The new energy policies target the reduction of fossil fuels, increase of energy efficiency, and integration of renewable sources, in order to reduce pollution and greenhouse gasses emission, reduce the dependency from mostly imported energy sources, and achieve a cleaner a sustainable energy system.

The European Commission has set the Renewable Energy Directive, which establish a common policy, for the countries inside the EU, for the promotion of renewable energy sources, where the main target is to achieve 20% reduction in greenhouse gasses emission, 20% renewable energy consumption, and 20% reduction in energy consumption by 2020, when compared to the levels in 1990. The plan includes the electricity, heating and cooling, and transport sector. Every country has different goals, ranging from Sweden (49%) to Malta (10%). The countries have adopted particular national renewable energy action plans to show they will meet their respective goals. On top of this, Denmark has set more ambitious goals, and the government intends to become 100% renewable by 2050, including both, the energy used for the electricity production and transportation sector.

So far, the effort of EU countries has been mostly concentrated on installing wind and photovoltaic power plants, although in comparison very little has been done on improving the system's efficiency and reducing the energy consumption.

What is clear is that the actions already taken, and the plans developed to fulfil the targets in 2020, are not enough to tackle the issue that initially made the EU to set new energy policies, the climate change. Therefore, when considering the long run, and the achievement of a cleaner and sustainable energy system, the way we handle the energy becomes as important as where it comes from.

For instance, what if, instead of focusing the effort mostly on how globally supply the energy demand with more renewable energy generation, we investigate on how the consumers can supply their own energy, and optimize the energy consumption, by becoming self-sustainable. Currently the actions are being taken at a big scale level, however, instead of considering country by country, we should probably go to a deeper level, and promote local energy production, region by region, town by town, building by building, or even home by home when it is feasible. Aside from the already studied benefits of moving the production closer to the consumption, an important, and not yet considered part, is to make the average population become more and more familiar with renewable energy technologies, and self-sustainability.

Regarding energy optimization at residential level, the future yields to the concept of Internet of Things (IoT), where all the home-devices will be able to interact with each other and the users, emphasizing on optimizing the energy consumption. The idea behind the IoT for home automation is that every device will be able to communicate and provide information to the consumer or Energy Management System

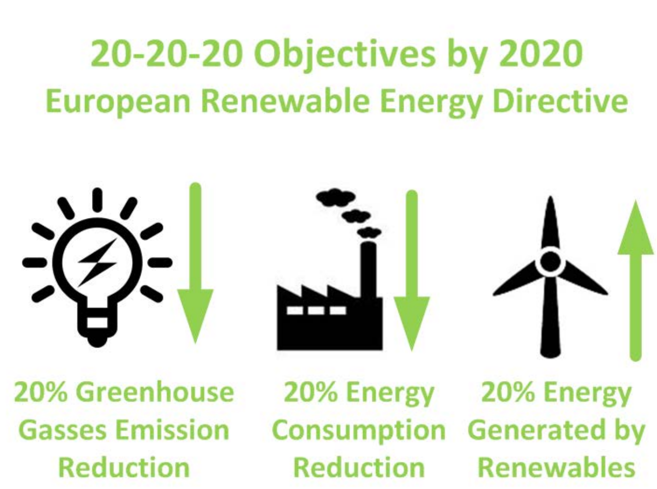

Fig. 1. European Union Energy Policy for 2020.

(EMS). Therefore, by collecting and monitoring consumption patterns, is easier to adjust the electricity demand and generation, especially when using renewable energy sources as PV and wind. Also, the consumer will be aware of their consumption, and therefore they can adjust their behavior accordingly, since a significant consumption reduction is achieved when the user is aware of the cost of the energy that is consuming [1]. Furthermore, the EMS can reduced the waste of energy caused by user´s bad habits, by turning off the lights in the areas in the house where there is no one, scheduling the heating/cooling system, so it does not work when the house is empty and so on. On top of that, the EMS would be able to decide the best time to run certain appliances, as dishwasher and washing machines, depending on the price or availability of the energy.

Hence, in order to achieve a sustainable energy system, the effort should not be mostly focused on the energy generation. The distribution of the energy needs to be done efficiently, and the wasteful of energy should be minimized.

II. DC AS TECHNOLOGY FOR FUTURE ELECTRICAL POWER SYSTEMS

An efficient distribution system is a key factor for sustainable energy systems. Nowadays, 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 the electrical power systems worldwide are AC-based. Nevertheless, today's scenario has changed, and DC based power systems offer interesting advantages regarding simplicity, cost reduction, and efficiency improvement [3].

DC technologies have been widely used in several applications and industries as automotive, aerospace, telecom, or electricity transmission. In the automotive industry 12VDC distribution system are used to distribute the energy and supply the electric/electronics equipment in the vehicles; in telecom applications 48VDC distribution systems are widely used; for long distance or undersea electricity transmission, High Voltage DC (HVDC) systems offer significant advantages over HVAC, furthermore, satellites have been using DC distribution system for quite a long time, since the only source of energy available up in the 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 advantageous, and the change of today's scenario makes those factors yield to a future DC distribution system.

The main factors which empower the use of DC systems instead of AC systems are:

- *DC Generation and Storage:* suitable renewable energy generators, as Photovoltaic Panels (PV) and Fuel Cells (FC), and energy storage systems, as batteries, are DC-based,
- *DC Loads:* The presence and consumption of DC loads is constantly increasing, due to the increment of electronic devices in building and homes,
- *Electric Vehicles:* the future integration of the electric vehicle in the power system, will increase the consumption of DC devices (batteries) in the buildings or homes,
- *Efficiency:* DC distribution systems are intrinsically more efficient than their AC counterparts, since in

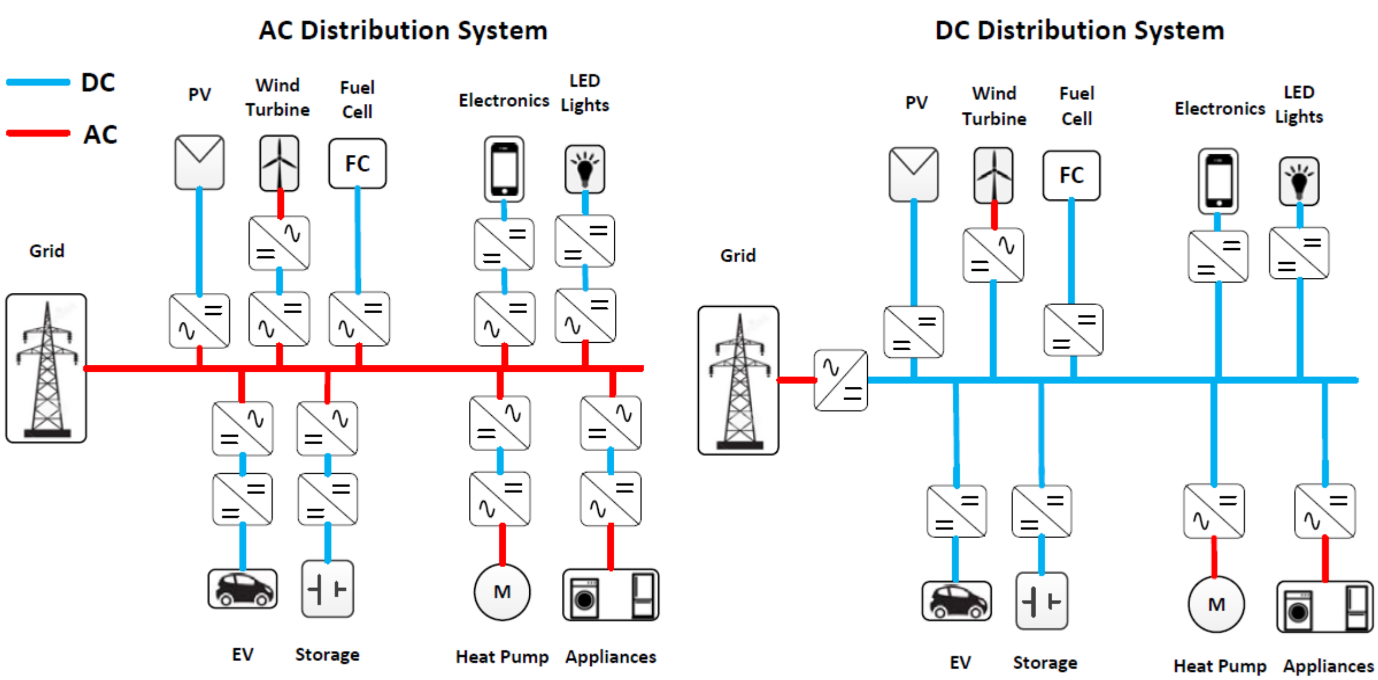

Fig. 2. Conversion stages reduction when switching from AC to DC distribution systems for residential applications.

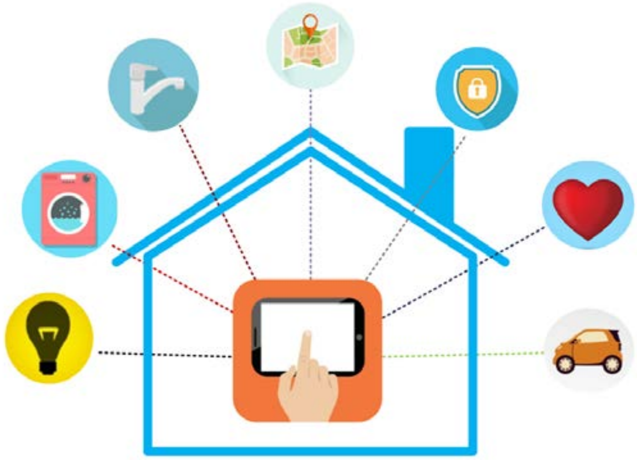

Fig. 3. IoT concept for residential applications.

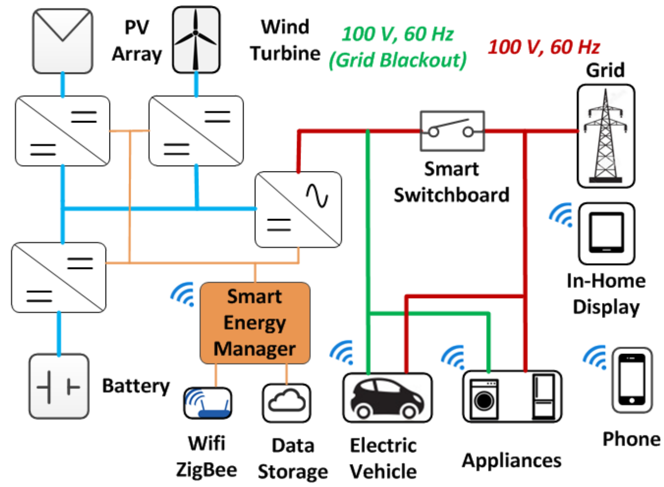

Fig. 4. Fukuoka Smart House.

DC there is not skin effect in the conductors, or reactive power loading the lines.

- *Conversion Stages Reduction:* interconnecting and distributing the energy between mostly DC-based agents (sources, loads, storage) through a DC power system avoids unnecessary DC-AC and AC-DC conversions which are a wasteful of energy.

Fig. 2 gives a clearer picture of the above mentioned aspects, showing the reduction of the conversion stages in the power converters of loads, 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 Renewable Energy Sources (RES), the conversion stages are reduced, however, in a real application the consumption and the generation are barely meet, therefore the energy consumed has been previously stored in the Energy Storage System (ESS), which does nothing but increase the potential energy savings implementing DC technologies.

Lately DC distribution systems have made their way into electrical power systems for industrial applications, especially in the telecommunication industry. In data centres, LVDC architectures have been widely studied [4], [5], and several facilities are currently using LVDC distribution systems. Data centres demand high reliable systems, where the integration of UPS systems is a priority, hence the installation of DC distribution systems reduce the conversion stages significantly, making the system more efficient.

In data centres the enhancement of energy efficiency comes with an extra advantage. The cooling systems are big part of the whole energy consumption, therefore by increasing the 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 the DC distribution systems also for industrial and residential applications seem like the next reasonable step, since several industries already benefit from tis advantages. Brian T. Patterson, founder of Emerge Alliance, has also shown the importance of the DC technology in a future electrical grid ”enernet”, and the Zero-Net-Energy buildings (ZEBs) [6].

There are few question that still need to be answered to see the true potential of DC distributions systems for residential applications

AC distribution systems have been recently losing ground against DC, however, when looking at residential applications, DC systems still have a long run ahead. The lacks of regulation and standardization, and 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.

III. Internet of Things 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, the overall efficiency of the system 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 reduced 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 bigger scales, and not only for home automation. For instance, when a city applies the IoT concept, both administration a citizens benefit from it, because the reduction of operational cost would bring an economical advantage for the city, and the citizens would see and enhancement of the quality of the services provided. The sector and services, that benefit from the IoT, range from the improvement of waste management, air quality enhancement, noise emission, traffic congestion and energy consumption reduction, parking availability and landmarks structural conservation improvement and so on [7]. The “Padova smart City” project seeks the experimental implementation of the IoT concept applied in a urban environment [8].

Going back to residential applications, the IoT at homes can be implemented by connecting several smart devices to a central EMS with decision-making capabilities. Once we start to interact with 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 as, the position of the people in the house, at what 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 and so on. Then, how can the EMS save energy by studying our habits? It can go from correcting bad-habits as leaving the lights on in room where there is no one or disconnect the heating system if there are windows or doors open, to scheduling the start-up of dishwasher or the washing machine depending on the price of the electricity, or the availability of the energy if there local renewable energy source installed in the home.

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

IV. 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 IoT, is the main issue when trying to implement such systems.

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

- *Connectivity:* There are quite a few communication standards being used in today´s devices, Bluethoot, Wifi, ZigBee, PLAN, therefore for the seamlessly integration of every device, new open source communication protocols are needed.
- *Consumption:* The power is critical for these applications since most of the devices run on batteries, and it is expected that they can run for years. The solution might be the used of harvested-power devices, which generate the energy from vibrations, light, or heat.
- *Security:* This is more of a social issue than technical. People are usually reluctant to share their information, and this goes against IoT principles, since the information in 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

Fig. 5. Intelligent DC Home in Aalborg University.

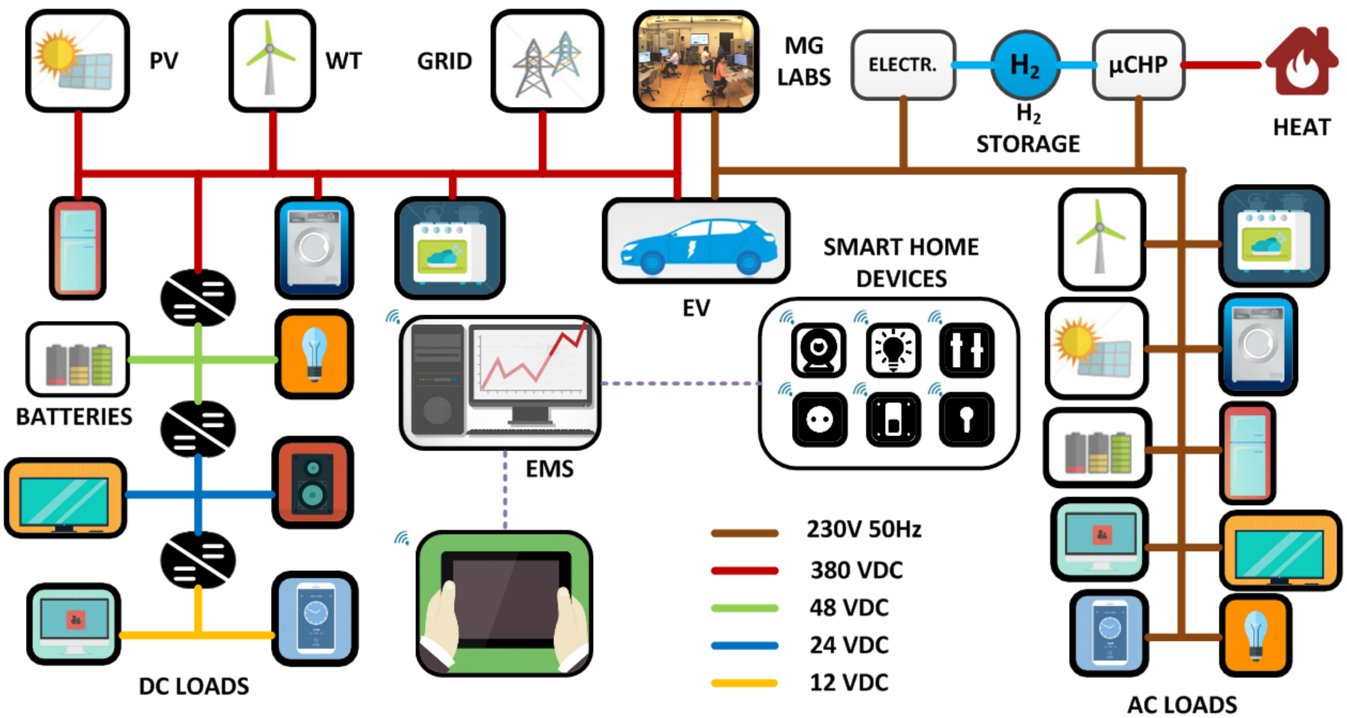

Fig. 6. Power Architecture of the Intelligent DC Home at Aalborg University.

need a common infrastructure formed by software and hardware, in order to reduce development costs, and boost the creation of IoT compatible devices.

On top of this, there particular challenges associated to the implementation of DC distribution system in residential applications.

- *Lack of Standards and Codes*: Several organizations as Emerge Alliance (EA), the European Telecommunications Standards Institute (ETSI), the International Electrotechnical Commission (IEC), IEEE and others, are already actively developing the necessary regulation 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 RES and ESS make the power flow to be bidirectional through the lines, hence, new schemes are required to detect and isolate the 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 barely commercial products ready to be used with DC voltage. For instance, in DC appliances/devices, small modifications are required to make them ”DC-ready”.

V. Prototypes of DC Homes

Generally speaking there are barely existing facilities, buildings or homes running on DC voltage, the supremacy of AC is complete. However, due to the interest and potential advantages, DC systems are focusing part of the 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 tsunami in 2011 that left most of the country with cuts in the electricity supply, the Japanese agenda has shift towards energy-independent or sustainable energy homes. For instance, in Tohoku Fukusi University in Sendai City, a microgrid has been implemented and it has been running since 2008 [9]. The microgrid has several local generation sources, gas engines and PV arrays, and energy storage systems formed by phosphoric acid fuel cell (PAFC). The facility in particular, and the technology in general, gathered the attention of the Japanese government, since it kept working autonomously from the grid during the earthquake in the 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. The facility was inaugurated in April 14th of 2012. The power architecture of the house is shown in Fig. 4. It consists of a hybrid AC-DC distribution system, renewable energy sources, an energy management system, 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, the energy storage systems.

Taiwan has also bet on DC for future more efficient distribution systems, in consequence, a demonstration facility has been built by the Elegant Power Application Research Center (EPARC). The system is formed by energy generators (PV panels, wind turbine and a fuel cell), energy storage devices (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.

In Aalborg University an Intelligent DC home is being implemented. The Danish Council for Strategic Research on sustainable Energy Environment has granted 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 investigate the energy saving potential, benefits and barriers of using directly electricity in DC form, from energy generated on-site, rather than converting it to AC for distribution. In other words, the systems shown in Fig. 2 are going to be implemented and studied.

The Intelligent DC Home will be divided in two different sections, both with fully functional appliances, electronics that are typically used at home, and smart homes devices. A central EMS control the energy flow within the facility, seeking for the optimization of the energy consumption.

VI. 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 all worldwide nations.

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 focusing on supplying the energy demand, reducing the demand itself would bring similar benefits. Hence, the implementation of the DC technologies for an efficient energy distribution, together with intelligent platforms for optimizing the resources and reducing the energy wasted, seems as the goal that we all need to walk towards to.

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