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Paramount importance of using distributed extra-low direct current voltage in the built environment

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Abstract: If solar panels and wind turbines can generate direct current (dc) voltage, and all electrical and electronic loads can operate directly off dc voltage, why is the distribution network within the built environment an alternating current (ac) system? In a world where carbon footprint is in focus, why are systems dc–ac–dc and not dc–dc–dc? Historically, voltage drop and therefore the need for larger gauge wiring were seen as technical and economic barriers to extra-low dc voltage systems. However, prices and power needs have lowered, it is now technically and economically feasible to use dc systems for the built environment. Such systems can provide energy independence and energy security. Examples of niche usage of solar photovoltaics that are providing electricity in the developing world are used to show that distributed dc voltage can have direct positive impacts on many of the UNs, sustainability development goals. Given the advantages of distributed dc electricity systems over centralised ac systems, it is concluded that policy makers and NGOs have to take on board dc as a sustainable solution to help the billions of people that either are not connected to electricity or use fossil fuels that are adversely effecting there health.

1 Introduction

Solar panels generate direct current (dc) electricity that is fed into an alternating current (ac) electricity distribution network, to supply electric power for consumption in end user loads. If the loads are electronic then they consume electricity as dc voltage. Therefore, in a conventional system, in order to supply dc voltage to electronic devices using renewable sources, there is the need for a twofold transformation, from dc to ac and then back from ac to dc. This double transformation requires an inverter and a transformer, both of which introduce losses into the system and increase its carbon footprint. By having a system that is only dc voltage, efficiencies can be gained.

Energy *efficiency* is synonymous with reduced consumption that can '*produce the same output or service*' [1]. Most of the UKs' domestic energy efficiency strategy has concentrated on measures that are connected to heat efficiency, [1, Box 2]. In this POSTNote [1], they only mention electricity in reference to the manufacturing and transportation sectors, but not within the domestic or public spaces environments. Present UK energy policy, therefore, focuses on energy efficiencies in general, but it does not put a strong emphasis on efficiencies within the electricity system of the domestic and small office environment.

In the UK the library at the University of Bath [2] had 50 computers that operated on 24 V dc, the data from which indicated that dc has advantages over an ac network [3, Section 5.6.2]. It is more resilient to external shocks that cause blackouts, and the third, fifth and seventh order harmonics associated with normal ac computer networks were significantly reduced. It is a smaller system and uses less energy than the original ac system, thus it has reduced bills and a smaller capital expenditure. Some similar advantages were found in the Bristol SoLa domestic dc project [4]. Therefore, by changing the whole system within the built environment to dc, energy efficiencies can be obtained.

However, many political and social scientists as well as many policymakers, are of the view that in order to deal with modern grand challenges a top-down approach is needed. They opt for what Karl Popper calls '*piecemeal social engineering*' [5]. They seek to change people's habits, through *behavioural*, *regulatory* and *economic* interventions [1], with little policy directed to innovations within the technology itself. Furthermore, such an approach has been followed for over 45 years since the publication of '*The Limits to Growth*' [6], yet many climate scientists continue to believe that the current trajectory of climate change mitigation is not reaching its target, thus the new lower proposed target of 1.5°C [7] in order to meet the Paris Agreement [8]. It is, therefore, time to now focus on the technology of the electricity system to initiate the required societal changes.

According to the GEA (2012, Section 5.2.2, p. 81) about half the world's population now live in urban areas, and it is projected that by 2050 this will reach ∼6.4 billion people. In 2008, the Chinese government predicted that by 2020 up to 65% of its population will be living in cities. Bai [9] predicted that this would mean 80 new cities the size of Nanjing. Similarly, in the UK, the building of brand new cities is on the policy agenda [10]. The denser the population, the greater the number of people who will be affected by any single loss of electricity, and therefore the greater the need for distributed electricity systems that can provide energy independence with security. This paper defines energy independence with security as '*the ability of a nation or a person to procure the raw materials and technology to generate enough energy to be able to keep themselves in their accustomed lifestyle without being dependent on another nation or person to provide this energy*'. Using distributed dc voltage systems will provide this energy independence and security at the home, office or small building level. Furthermore, given the ubiquitous nature of electricity to the functionality of modern societies, and its potential use in the developing world, this paper identifiers dc distributed electricity systems as a technical solution to help achieve the 17 UNs' sustainable development goals SDGs [11].

The historical context of the continual use of dc voltage within the electricity system is highlighted in Section 2, and at this time, there are many dc voltage ready technologies (Section 3) that can be used as part of an extra low dc voltage system. Previous research identified the electricity system as sociotechnical [3], this implies that it has wide ranging effects on societal issues. These societal issues are encapsulated in the UN's sustainable development goals for 2030 (Section 4). Based on two papers that looked at over 100 case studies of interventions in the developing world, this paper explores some examples of the use of solar electricity for the following: (i) to enhance economic activity, (ii) for solar lights, (iii) as a means to decrease the wastage of food thus to help end hunger and achieve food security, to help make the

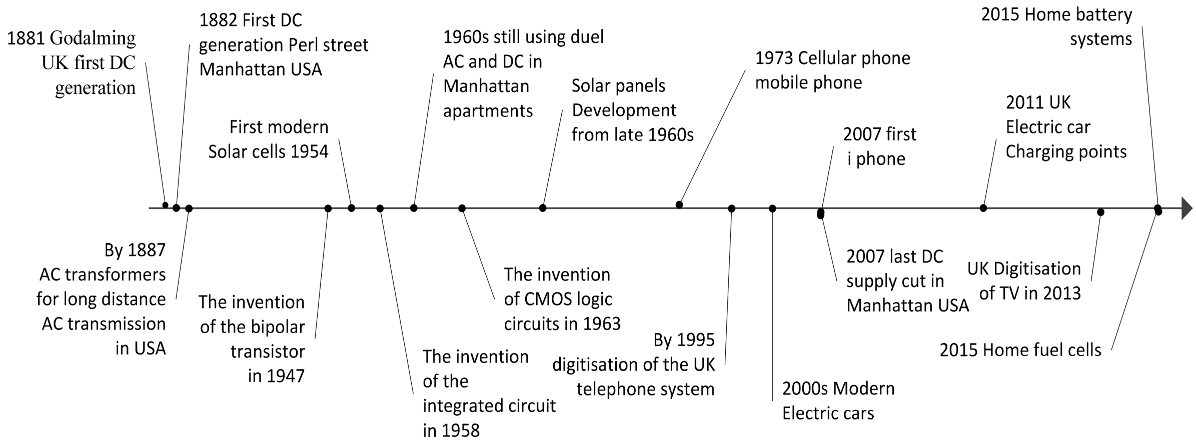

Fig. 1 *Timeline showing major milestones in the electricity system over the last 136 years [3]*

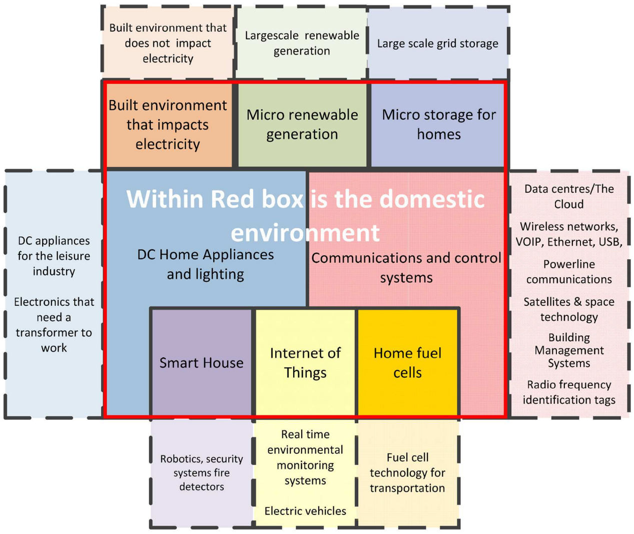

Fig. 2 *Available technology that could be used in a dc electric home [3]*

(iv) healthcare and (v) education systems more able to help people in the developing world, (vi) to enhance gender equality, (vii) to alleviate pressures on forests and oceans ecosystems and (viii) to become energy independence thus positively impacting geopolitics around the world. It is concluded (Section 5) that it is of paramount importance for the future usability of the built environment in the developing world, that a full distributed dc voltage renewable system should be adopted as the de-facto standard.

2 Historical context of the modern electrical system

Godalming was the first town in the UK to have a public electricity supply system in October of 1881 Gordon [12, p. 15]. This was before Edison set up, his Perl Street electrical generators in September 1882 [13]. At the outset, Edison was generating the electricity in the form of dc voltage. As his customer base increased further away from his generators it became apparent that, at long distances, distributing dc voltage had the technical issue of voltage drop [14, section 2.3.6]. While Edison continued advocating dc electrical systems, Westinghouse together with Tesla, advocated the use of ac electricity systems [15], which do not suffer from voltage drop at transmission voltages.

By 1887 the development of the transformer allowed for the easy stepping up and down of ac voltage [12]. Thus by 1898 [13, p. 113] Edison was supplying ac electricity to his thousands of customers, and converting it to dc to be consumed as dc voltage. Many of the Manhattan apartment buildings had duel ac and dc electrical supplies in each apartment until the middle of the 1960s. For these customers, the Edison Company manufactured dc home appliances. Although for over a century, a centralised ac voltage generation and distribution system has been the dominant and in most countries the only technology, the use of dc voltage electricity has had continual niche applications from the 1880s. In 2007 the last dc supply line was cut by the Consolidated Edison Company in New York, after which the dc loads were supplied from the ac network via a transformer [16].

With the advent of electronic technology, the electricity system has come full circle where many loads now consume dc voltage (see Fig. 1). Since 2015, the 'Maslow' [17], 'Power Wall' [18] and 'Solarwatt' [19] battery systems have entered the domestic market. Thus solar photovoltaics (PVs), together with the home battery systems are able to form the basis for the future dc home. Add to this hydrogen fuel cells, that already exist within the petrochemical and transport sectors and smart microgrid technology, dc voltage generation and transmission technology is already here. Nevertheless, the question remains if the ac system had been operating all over the world for so long, why is there a need to develop and use dc voltage, and why now? The answer is to look at Fig. 1. It shows, that since the invention of the bipolar transistor, technology is moving towards the use of low powered power-electronics for many of our electricity consumption needs. However, at this time not all loads are electronic. In the next section, some of the available technologies that can be used in the dc voltage system for the built environment will be explored.

3 Technology

3.1 Available dc technology for the built environment

At this time, renewable dc voltage generation technology and the means for electrical storage in batteries, exist as off-the-shelf products. While the range of available dc enabled household appliances [20] is limited compared to the amount of off-the-shelf ac household appliances, they are increasing all the time. Furthermore, there are many diverse technologies that are cutting edge and niche, that can be used within the dc electricity system in the residential and office sector. For example, home area networks [21] the Internet of Things [22] that use data communications over wireless, Ethernet, or the electricity mains, which uses Power Line Communication protocols [23–26]. At this time, in 2018, there are many competing/complementary smart-house technologies, based on the IEEE 802 family of standards [27, 28] and the HomePNA [29] based on IEEE 901 standard. Building management control systems already have the ability to monitor and gather data on many characteristics of the building including the electricity system. Data acquisition and control systems include Supervisory Control and Data Acquisition systems (SCADA) [30], and some of the home and building controls technology in KNX and X-10 standards [31, 32], as well as many more, can be used within the dc home. Some of these technologies are set out in Fig. 2.

The red box in the centre of Fig. 2 represents the available areas of technology within the built environment, whereas outside this box are areas where the technologies are used for non-domestic applications. At this time much of this dc technology is only in niche applications. Incorporating these technologies into a dc voltage home will catalyse its proliferation into the mainstream mass market. Furthermore, as both the price of distributed generation, and the energy requirements of most appliances, continue to drop, it is now more technically and economically feasible to use dc-only electricity systems within the built environment.

Traditionally, voltage drop and therefore the need for larger gauge wiring were seen as technical and economic barriers to extra-low dc voltage systems [33]. However, based on the 2050 average size residence in the UK [34], previous research has shown that the voltage drop is manageable in the extra-low dc voltage home [14, 35]. Therefore, from the technological standpoint, the dc voltage home or small office is possible once dc technical standards have been established [3]. Furthermore, there are billions of people in the developed world who live in single storey houses as well as those in the developing world who live in relatively small houses, all of whom can take full advantage of dc voltage without the need to worry about voltage drop [35, Section 5.4.0]. Therefore, there are advantages of using a distributed extra-low dc voltage system over a centralised ac voltage system.

3.2 Some reasons and advantages for distributed extra-low dc voltage

In summary, the technical economics and societal advantages of using dc voltage [3, 35] are as follows:

Technical

i. Electronic appliances do not need an ac-to-dc converter. Therefore, they will have a smaller carbon footprint, and cost less to manufacture than their ac equivalents.
ii. dc appliances should use less power than their ac equivalents. Therefore, the size of the renewable energy generators needed to the power building will be smaller. This decreases the costs of the electricity system.
iii. White goods can and do operate on dc voltage.
iv. dc only systems eliminate the inverter and all the external and internal lossy ac-to-dc converters.
v. dc technology have less moving parts, are more robust, and last longer than ac equivalents.
vi. LED and halogen lights operate directly off dc voltage.

Economic

i. With economies of scale in manufacture, the price for dc appliances should be the same as ac appliances.
ii. Proliferation of dc systems offers the opportunity for economic growth.

Societal

i. For the 1.1 billion people who are not connected to an electric grid [36], a dc home should give them a large increase in living standards quicker and cheaper than a complete centralised ac grid connection.
ii. Decentralised energy generation from renewables with storage, greatly increases energy security and energy independence for the householder and for the country.
iii. A distributed electricity system can increase a city's resilience, and reduce cascading effects in times of national disasters.

Given the advantages that distributed dc voltage can offer, this paper is proposing that it should be considered as an alternative for ac within the built environment. This is not only because of the availability of dc technology but also because of its potential use as a solution for many of today's societal challenges that have been encapsulated in the UNs' 17 SDGs.

4 UNs' sustainable development goals

The use of electricity in cities is not limited to providing energy for the functionality of a city's infrastructures, it is also integral in providing the standard of living expected in the developed world. Therefore, this paper proposes the use of distributed dc voltage systems to enhance a city's resilience against failures of the centralised grid. For the billions of people who are either not yet connected a national grid or who or do not have a constant adequate supply, they could be provided with a distributed dc system and completely leapfrog the national grid. By using a bottom up approach, it is proposed that many of the UN's 17 SDGs [11], can be made more achievable. However, it must be noted that the use of electricity will have different impacts on each gaol; some goals will be impacted more than others. Note: Within the narrative is embedded, within brackets and highlighted in bold, the relevant goal that the narrative is focusing on.

It is not possible within this paper to write a full description of how distributed dc electricity systems can help towards achieving all these 17 SDGs. Each goal deserves a paper on its own. However, what is written here are some examples of possible interventions and a comprehensive discussion is left for further work. It draws on two literature review papers [37, 38] that looked at over 100 case study documents from all over the world, for projects aimed at providing electricity to those that received an electric connection for the first time. The goal of this paper is, therefore; to open a debate as the paramount importance of using off-grid distributed extra-low direct current voltage as solutions for these SDGs.

When a districted dc voltage system is used as part of an intervention, it is important to provide adequate power for the expected outcome. Therefore, the amount of electrical power provided and the expected outcome must be in line with the IEA and World Banks' six tiers of electrical provision [39]. Otherwise, a mismatch between the expected outcome and the amount of energy provided will be misinterpreted as a failure, as was concluded by Aklin *et al.* [40] from their case study of the Mera Gao Power system, a Tier 2 provision, that only included LED lights and a mobile phone charger [41]. The minimum power provision for each tier is as follows; Tier 0 no power provided, Tier 1 3 W, Tier 2 50 W, Tier 3 200 W, Tier 4 800 W and Tier 5 2 kW.

The quality of life of city dwellers is dependent on a city's resilience, something very much dependant on electricity. Veenhoven [42] defines the '*liveability*' of a nation as '*the degree to which its provisions and requirements fit with the needs and capacities of its citizens'*. This means that liveability is about the standard of living citizens expect within the society in which they live. Therefore, having constant access to electricity is fundamental to modern living. However, there is an inherent vulnerability within the centralised topology of the electricity system, that as one of the critical infrastructures [43, 44], if it fails, it causes massive cascading effects [45, 46] that then causes failures in other interdependent infrastructures [47, 48]. Furthermore, there is the cyber security issue associated with smart grids that can quickly cause catastrophic further failures [49]. Therefore, just like power outages have huge ramifications to a developed world city's resilience (**Goal 11**), providing distributed dc voltage to cities in the developing world will increase their resilience and help towards many of the sustainable development goals

4.1 Use of electricity to enhance economic activity

Electricity underpins the ability to undertake many economic activities that impact on a country's ability to grow its economy. The conclusion as to the causality between energy usage and economic growth [50, p. 399] is ambiguous. Lee [51] concludes that the energy use generally causes GDP growth, while Wang and Xi [52] conclude that although they are both interrelated and GDP drives energy growth, energy has little effect on GDP. Research carried out on several African countries [53], found the existence of causality between energy and economic growth in 15 out of 17 countries.

Whatever the view about the correlation between GDP **growth** and energy, by implication, those that do not yet have access to electricity are not able to take advantage of using electricity to enhance their income. Furthermore, those that live in parts of the developing world where the grid cannot provide an 'all the time all year round' service, intermittent supply or black outs will negatively impact there economic activities. In fact, when a power cut occurs, however small, there will be an associated economic cost [54]. Andersen and Dalgaard [55] estimate that power outages between 1995 and 2007 in South Africa '...show that the economic impact is likely to have been substantial'. There are estimates for losses in Germany [56], Ireland [57], Scotland [58], and the USA [59] which can be very high for industry. Praktiknjo *et al.* [60] estimate the cost to domestic customers in Germany to be on average 15.70 €/kWh, while for commercial, industrial and governmental consumers it is 6.00 €/kWh. Besides the monetary costs, there is also the social costs connected to the impact on people's living standards. Therefore, providing off grid renewable low power dc voltage systems, even at Tier 4, besides providing levels of access to affordable, reliable, sustainable and modern energy for all (**Goal 7**), they can also help mitigate against poverty (**Goal 1**) [61–63], and increase economic activity that promotes social inclusion (**Goal 8**).

The classic use of electricity (at the World Banks' Tier 5) to grow the economy through the provision of electricity (**Goal 8**), is the 'Red Wing Project' [64], a project that ultimately led to the provision of electricity and electrical appliances to millions of Americans [65] and brought down the cost of extending the rural electric grid (Beall, 1940). One secondary effect of growing a country's GDP is to begin to address the economic disparity (**Goal 10**) between developed and developing countries. This is corroborated by Rao *et al.* [66] who state with regard to renewable energy systems that

> '…The more these systems can be encouraged to support a broader set of services, particularly productive uses, the greater the potential for off-grid systems to serve as a mechanism for rural development'

4.2 Solar lights

Kerosene is used to light up homes all over the developing world. However, this is being challenged. An example of a Tier 2 provision that is targeted at eliminating the use of Kerosene [41, 67–69] is solar lamps [70, 71]. According to Aevarsdottir *et al.* [72], households who received a solar lamp that included a mobile phone charger saw a 20–30% increase in their income. (**Goals 3, 7 and 11**). Furthermore, by providing solar lamps it reduces the ecological damage caused by the prolific use and non-recycling of dry-cell batteries [73] (**Goal 12**) and gives children more time at home to study in a nontoxic lit environment [66] (**Goal 4**).

The solar lights can be used at night by business owners to do business administration. And if the whole village has access to electricity and public spaces are lighten up, then small business can take advantage of customers coming in the dark hours (**Goal 8**). Similarly, it was found that farmers used their lamps to check on their animals at night to prevent theft [72] (**Goal 11**). This shows that there are other positive outcomes from providing electricity to small business owners other than an increase in income. If these economic and social advantages were found just by providing solar lamps with batteries, how much more so if a Tier 5 system could be provided.

4.3 End hunger and achieve food security

In India alone, 21 Million tonnes of wheat has been wasted each year due to inadequate storage and distribution, and it is estimated that up to 50% of food produced never gets eaten due to crop wastage and food Spoilage [74], (**Goals 2 and 12).** Inadequate refrigeration [75] and cold transportations [76, 77] exacerbate the problem. Dearman states that there is a need to improve the 'cold chain' within the built environment in the developed world, how much more so in the developing world, where there is malnutrition and high food prices [78]. This paper offers the solution to use off grid mobile distributed dc voltage systems to dry grains and pulses, thus stopping rot and mould. If dry storage provides a large proportion of this spoilage could be reduced. Also by providing distributed dc voltage systems the usage of diesel-based cold chains that dominate refrigeration in many countries could be leapfrogged by developing nations [76], thus improving air quality (**Goals 11 and 13**).

4.4 Healthcare

In the literature, between 1992 and 2010 several instances of total electrical failure within hospitals, where even the emergency backup system failed, have been documented [79–85]. These instances are in developed world countries. If distributed dc voltage systems were employed all over the world in medical facilities, the health and wellbeing of many people will be improved (**Goal 3**). Furthermore, there are many people who have lifesaving medical equipment at home, e.g. dialysis machines. During Hurricane Sandy, when the electricity to many New York apartment building went off for many days, these dialysis patients suffered [86]. With the use of off-grid electricity systems, not only will it secure the health and wellbeing in the developed world (**Goal 3**), but it would be possible to provide non-fossil fuel based solutions (**Goals 11 and 13**) in places where the national grid has not yet reached. The provision of off-grid refrigeration is required for many vaccines, antibiotics, blood, and medication that require to be chilled otherwise their effective lifespan is much reduced (**Goal 3**).

4.5 Education

Besides solar lamps enhancing the ability of children to do homework, LED lights together with computers operating off extra-low dc voltage electricity systems, are used to enhance the educational opportunities for many children and adults in the developing world [87–89] (**Goal 4**).

4.6 Gender equality

Given the ubiquitous nature of electricity in the functioning of society, it is important to focus on how the provision of electricity within the developing world can help to achieve gender equality and empower all women and girls (**Goal 5**). Part of the daily routine for many women and girls is the time consuming and physically demanding work of bringing water into the household. In some part of the world, the only water available is surface water that is polluted or contaminated [90]. However, there is a drive via international NGOs, to install off grid solar powered pumps [91, 92] in order to provide clean ground water (**Goal 6**) close to where people need it [93]. These pumps can also be used to take away waste water, which helps to reduce the incidence of waterborne diseases amongst poor people [90] (**Goal 3**). To provide a means whereby women do not need to carry the water, Watt-r [94] have invented a solar powered cart that a single person can use to transport up to twelve 20-litre containers of water at a time (**Goals 1, 5, 6 and 8**). Grimm *et al.* [95] found that providing PV lamps allowed people to use them during the day for their normal housework activities (Goal 5). In Dharnai India, the provision of 60 solar street lights, not only had the benefits of increases economic activity during the dark hours but woman and girls gained increasing access to both public and personal spaces after dark [96] (**Goals 5, 7, 9 and 11**).

4.7 Forests and oceans

Ways must be found to provide dc voltage systems that could provide the power needed (**Goal 7**) for off-grid cooking and heating purposes. This would reduce the number of fossil fuels used (**Goal 15**) by the 3 billion people that use them for cooking, increase the air quality (**Goal 11**) in homes [50] and reduce carbon emissions (**Goal 13**).

The use of dc voltage in ships is not new [97]. However, these ships only use dc voltage to power the on-board systems and lights, but not as a means of propulsion. Now, Eco Marine Power [98], are opting for a completely sustainable ship powered by renewable energy (**Goal 14**).

4.8 Geopolitics and energy independence

Much has been written about the use of energy as a political weapon [99–103]. In the USA the goal of energy security and energy independence has been pivotal to their energy policy [104, 105, p. 160, 106]. Therefore, this paper puts forward the argument that if distributed dc voltage systems were used to gain energy independence across the whole world, the geopolitical situation across the world may be in a much better position. Perhaps world peace (**Goal 16**) would be enhanced and therefore governments would be more willing to work together in implementing these SDGs (**Gaol 17**). Furthermore, it is postulated, that the huge demographic movement of economic migrants that has been taking place in the last decade could possibly be regressed if the distributed dc voltage systems are used to enhance people's quality of life and socioeconomic level in their own home. Also, the demographic movement from rural areas to cities may slow down and reverse, if distributed electricity systems are used to provide adequate economic prosperity in the villages and small rural towns.

From the many case studies in the literature and from the websites of many NGOs it has been possible to find many ordinary and many niches uses for off-grid solar systems throughout the world. While many interventions are only Tier 2, the case studies show that they make small but significant impacts on the lives of many people. What is now needed is, that the UN and national governments should recognise the importance of including into their solutions Tier 5 off-grid distributed dc voltage systems, in order to help transform the lives of millions of people.

5 Conclusion and further work

This complex world that we live in has its grand challenges, some of which mankind has been struggling with for nearly half a century. Throughout this time, energy and the electricity system have been in focus, in order to reduce its carbon footprint and the amount of energy used by electric and electronic loads. However, policy makers have placed little emphasis on radically changing the actual system, but have rather opted for behavioural, regulatory and economic interventions. This paper, therefore, concludes, that more emphasis must be placed on changing the technology of the whole electricity system, especially at the point of end user consumption.

Within the historical context of some of the electricity systems in the developed world, dc voltage has always been present. However, it has been within niche applications or consumed in electronic devices, yet in grid connected scenarios, the dc loads have been fed from an ac voltage generation and distribution system. This paper concludes that given the availability of current technology, now is the time that a full dc voltage generation distribution and consumption system should be employed to power the extra-low power home and office. While such a solution seems out of place within the developed world, this paper has discussed the cascading effects of power cuts within the centralised system on other critical systems that only operate with electricity. Thus there are some advantages even in the developed world to use off-grid distributed dc voltage systems.

Given that there are over one billion people who do not yet have access to electricity, and 3 billion that use fossil fuels to cook, distributed dc systems offer a quicker solution than waiting for a national grid to be developed. Providing such systems costs money and will require more research and innovation, therefore policymakers, NGOs and the business world, need to be persuaded of its positive contributions for society. Therefore, this paper discussed how distributed dc voltage systems can be used as solutions towards achieving the UN's 17 SDGs. Therefore, it is important to take into consideration the impacts on society that distributed dc voltage systems can provide, beside the technical advantages.

Based on previous research, what is needed is further research and development into an optimised dc voltage specification as well as for more innovation to make electric loads dc voltage ready. However, the research for such systems, being cross-disciplinary, is plagues with under investment and a lack of focus. Knowledge transfer between engineers and scientist is therefore paramount and more focus and financial aid are needed from policy makers to make dc voltage a reality that can change the living standards of billions of people. This paper concludes that it is of paramount importance for society, that more focus is placed on implementing the use of distributed extra-low dc voltage in the built environment.

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