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Review

The Role of Off-Grid Houses in the Energy Transition with a Case Study in the Netherlands

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Abstract: Off-grid houses can be considered an important concept to increase the access to electricity throughout the world. Although there are quite some initiatives in place to improve the access to electricity, the implementation rate of practical solutions is far below the UN Sustainable Development Goal 7: Energy (SDG 7) + for 2030. This situation is most apparent in Sub-Saharan Africa, where the current trends of electricity access calculated by the World Bank indicate that this region will not be able to achieve the SDG 7 target. Another worldwide trend which may help to increase electricity access is that currently, a lot of renewable energy generation is realized locally in houses (especially Solar Photovoltaics (PV)). This paper reviews the recent developments to increase the access to electricity in the world and the implementation of off-grid houses in different scenarios. The focus here is on the different efforts to create off-grid houses considering their challenges on a macro and micro level. Moreover, potential research directions for technologies in off-grid houses are presented in more detail. For this, a case description of a possible off-grid house in the Netherlands is presented together with some initial simulations results for this case using solar PV, the Sea-Salt battery, and a Glycerol Fuel Cell. The simulations use the DEMkit software and the analysis is performed using measured house load data for a period in winter and in summer.

Keywords: electricity access; solar PV; off-grid house; sustainable development goals; sea-salt battery; glycerol fuel cell

1. Introduction

Houses not connected to the electricity grid or being able to (almost) operate without the electricity grid (i.e., off-grid houses) may become an important element in the future electricity infrastructure. On the one hand, as worldwide the access to electricity inside homes is an important element for creating quality of life, off-grid houses may enable such an access in regions without a proper grid infrastructure [1]. On the other hand, due to the possible consequences of a worldwide climate change, the vast majority of countries are making plans towards a massive introduction of renewable energy—especially solar photovoltaics and wind turbines. This massive introduction of renewable energy leads on the one hand to local energy generation but on the other hand also to a lot of challenges that need to be overcome. In this context, off-grid houses may be an element that can support the integration as they tend to keep generated energy locally. These two topics lead to two opposite trends of developing and implementing off-grid houses, the top-down approach and the bottom-up approach.

The top-down approach refers to the countries that currently already have a stable connection to the electricity grid and want to introduce more renewable energy in the existing system. This applies to developed countries, but also to the main cities in the majority of the developing countries (stable connection refers to a connection to the grid with power shortages of less than 300min/year [2]). In the Netherlands, energy-neutral houses are supported by current net-metering schemes. If a house owner purchases a large setup of solar PV, net-metering implies that at the end of the year, the total electricity bill will be determined based on the difference between the total electricity production volume and total electricity consumption volume [3]. However, the system of net metering of solar PV is now under change due to their costs for the government, but also due to the negative effect on stabilizing the electricity system. It is expected that by 2023, a feedback tariff for end users will be introduced that will be much lower than the tariff for the electricity consumed [4].

However, there are also regions where the electricity grid is non-existent or exists but is not stable or reliable [1]. For example, in Sub-Saharan African countries, current solutions are implemented to connect more cities and rural areas to the main grid [5]. However, in this part of Africa, a large investment and a lot of infrastructure is needed to realize this connection. Considering the current local economic trends in these areas, it seems that there are not enough possibilities to increase electricity access in this way. On the other hand, environmental policies and the data from the utility providers shows that there is also a tendency in these regions towards the introduction of a considerable amount of renewable energy, such as solar photovoltaic (PV), wind turbines, among others. In particular, solar PV is a flexible and easy-to-use technology that provides electricity on the spot without the need for a complex electricity infrastructure. Here, a bottom-up approach for implementation of a 100% off-grid house may be used, meaning that off-grid houses may be implemented using solar PV and lead acid batteries. These off-grid houses therefore may also be seen as innovative ways of fast implementation of renewables. Examples for such developments are systems combining solar PV, batteries, and television systems in Tanzania and Kenya, which use mobile tariff apps for pricing, allowing users to pay for their electricity [6]. Another example is in Bangladesh, where by using a swarm electrification method, it has been possible to implement solar PV and batteries to low-income villages [7]. The basic idea is to set up a local economy in a small village. Initially, electricity is provided to one of the businesses using only a small investment (e.g., for one solar panel and one LED light to work when it is dark). This business may be able to start sharing the electricity produced by the panels with its neighbors, for which it would get some sort of fee. Adding these customers may help the first business to buy more solar PV, and in the end, it could expand the grid slowly, until reaching a village with lights in all houses. Currently, this approach still is in the developmental stage, and fare tariffs are a matter of discussion.

Both cases, the top-down and bottom-up approach, show that there is a tendency towards the implementation of solutions where houses or groups of houses produce (a large part of) their electricity for their own usage, with a tendency to create 100% off-grid solutions, at least for a large fraction of the time. Furthermore, in all of these cases, electricity storage is seen as an important asset.

The goal of this paper is to review the most recent advances in access to electricity in the world and to review the literature that supports the implementation of off-grid houses in different scenarios. We present an overview of different efforts to create off-grid houses considering both the top-down and the bottom-up approach. Moreover, some potential research directions for technologies in off-grid houses are presented in more detail. This paper is organized as follows. In Section 2, we give a short overview of the United Nations Sustainable Development Goals and how they are connected with electricity access. In Section 3, we give a brief overview of the worldwide electricity access. In Section 4, the developments of electricity grids in developed countries is discussed followed by an explanation of different types of off-grid solutions in Section 5. In Section 6, the challenges of off-grid electrification are described, and in Section 7, a possible set up for a standalone off-grid house is presented. In Section 8, the results of a case study of a stand-alone off-grid house is presented using new technologies and data from a real house in the Netherlands. Finally, some conclusions are drawn in Section 9.

2. UN Sustainability Goals for 2030 with a Focus on Goal 7

Worldwide electricity access is necessary in order to reduce poverty, since without electricity, the development of countries tends to be slow and complicated. Currently, there is considerable economic progress in terms of the energy infrastructure. However, this growth is not fast enough, and therefore, the United Nations (UN) Sustainable Development Goals (SDGs) have been defined [8]. The SDGs have 17 main topics that are part of the 2030 Agenda for Sustainable Development, adopted in September 2015. In this 2030 agenda countries agreed in creating a set of goals to end poverty, protect the planet, and ensure prosperity for all as part of a new sustainable development. Each of the goals has specific targets to be achieved over the next years. To achieve these goals, all the relevant stakeholders have to be involved: governments, the private sector, civil society, and individuals. The SDGs are distinctive because they include the contributions of all countries, independent of their social situation (rich, middle-income, or poor). The goals show that ending poverty is a process that goes together with methods and strategies to address social needs promoting economic growth while protecting the environment and climate change.

In case of energy, the World Bank estimates that one billion people (approx. 13% of the population in the world as of 2017) are living without access to electricity, and around 40% of the people in the world cook with fossil fuels in polluting conditions [9]. This situation diminishes their health and quality of life and, therefore, the United Nations have placed universal access to electrification and the use of clean technologies for cooking in the energy targets of the SDGs, with the intention to accomplish this by 2030 [8].

One of the 17 SDGs is Energy (SDG 7), which does not only cover problems related to limited access to electricity, but also involves a more global framework. The SDG 7 calls for three main action points:

1. Access to universal and modern energy services.
2. Double the improvement in energy efficiency.
3. Double the share of renewable energy in global energy production.

These three action points were first mentioned in 2011 by the Sustainable Energy for All (SEforAll) initiative [10] and were adapted/included in the SDG 7 targets. In detail, the SDG 7 is targeting the following goals:

- By 2030, ensure universal access to affordable, reliable, and modern energy services.
- By 2030, increase substantially the share of renewable energy in the global energy mix.
- By 2030, double the global rate of improvement in energy efficiency.
- By 2030, enhance international cooperation to facilitate access to clean energy and technology development, including renewable energy, energy efficiency, and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology.
- By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular in the least developed countries, Small Island Developing States, and land-locked developing countries, in accordance with their respective programs of support.

These five targets indicate the areas where policies must be developed, (e.g., increasing the share for renewable energies in the global energy picture, and also improving the rate of implementation of energy efficient technologies). However, the SDG 7 Energy is interconnected with all the other 16 SDGs, and it is linked to 125 out of 169 targets of the SDGs, which account for almost 74% of the total targets. Nowadays, it is globally recognized that planning for universal access to modern electricity is a primary goal in the national plan for the development of countries and the SDGs [11].

Studies by the World Bank on power blackouts indicate that loss of electricity leads to a loss of economic value in communities [12]. For example, in Tanzania during 2012, power blackouts cost businesses around 15% of their annual sales. Furthermore, when electricity is stable and available, this leads to more income, work, and education for individuals in communities [13]. Additionally, when modern electricity is not available, this creates constrains on economic growth, but when it is stable and available, it increases growth and employment opportunities.

3. Overview of the Worldwide Electricity Access

In this section, we give a short overview of the electricity access, with respect to the lack of electricity in different parts of the world. Calculations by the World Bank in 2014 showed that the electricity access deficit (people without access to electricity) is mostly concentrated in Africa and South Asia, rather than in other places in the world. The most affected area is the Sub-Saharan Africa, in which it is estimated that 62.5% of the people do not have access to electricity [14]. In total, around one billion people are without access to electricity (see Figure 1), of which 20% are in South Asia, 60% in Sub-Sharan Africa, and the rest distributed in the Pacific, East Asia, Latin America, Middle East, and North Africa.

Figure 1. Access to electricity (% of population) World Bank, Sustainable Energy for All (SE4ALL) database from the SE4ALL Global Tracking Framework led jointly by the World Bank [11].

The IEA (International Energy Agency) estimates that at the country level alone, India has more or less one third of the global deficit of electricity (270 million people), followed by Nigeria and Ethiopia [15]. Figure 2 shows the evolution of the percentage of population with electricity access in the different regions of the world from 1990 to 2016, with a projection towards 2030. In between 1990 and 2016, it may be noted that there has been a large improvement in access to electricity on a global view, and this increase in coverage occurred in both cities and rural areas.

In the US, Europe, and Central Asia, the access to electricity is approaching 98%, and this is already in line with the 2030 targets for development. East Asia & the Pacific, Middle East & North Africa, and Latin America & the Caribbean show a constant improvement since 1990, and it is expected that by 2025, the energy access will be covered in cities and in rural areas, if political conditions and economic growth have the same trends as in the last decade. Also, in South Asia, the access to electricity shows a constant increase during the years 1990 to 2016.

The trend indicates that by 2030, most cities will be able to reach the stated goals. On the other hand, rural areas in South Asia are falling short in the current trend, showing that in 2016, the coverage was 80 % in cities and 70% in rural areas. The situation in South Asia is similar to Sub-Saharan Africa; however, Sub-Saharan African countries have the lowest access in electricity in both cities (30%) and rural areas (20%). At the current rate of development, South Asia might be able to achieve the 2030 target. On the other hand, Sub-Saharan Africa at the current rate of economic development will not be able to reach the target. Sub-Saharan Africa is growing 5.4% annually against the needed 8.4% annually to reach the 2030 goal [5].

It was observed that electricity access improvement in the world by 2014 was almost the case all in urban areas. Furthermore, the expected population growth of 1.5 billion by 2030 will create a growth in urban cities, and this will be reflected in rural to urban migration [16]. This issue implies that rural population will not increase considerably, but will probably remain stable. Although from a global perspective, rural migration to cities may suggest an easier connection to electricity grids, the migration often leads to increasing presence of slums, which are in general not well connected to the basic infrastructures. This increasing demand in slums will require strong regulation, investments, and infrastructure to warrant enough electricity in future urban slums.

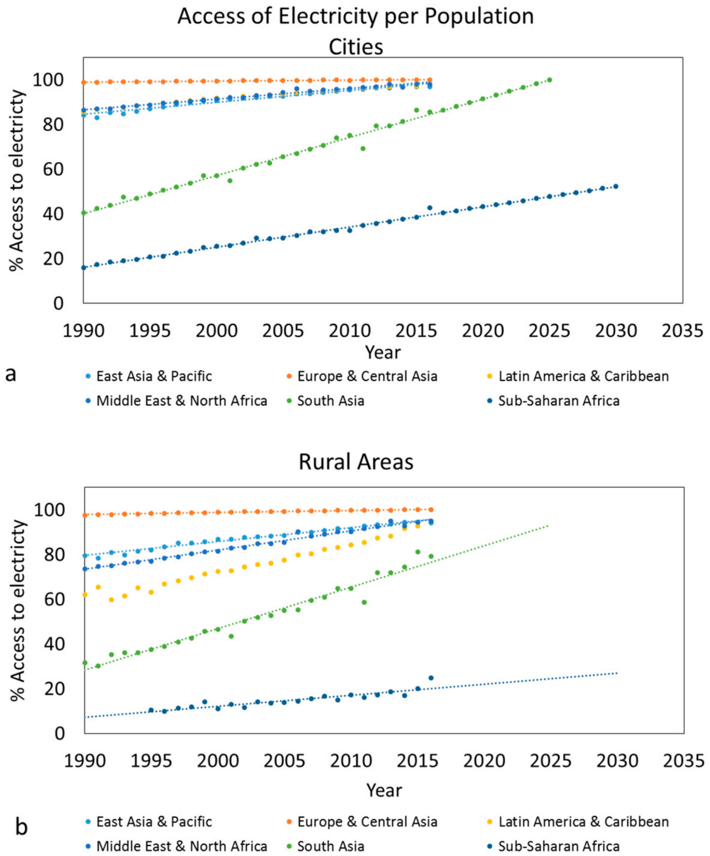

Figure 2. Percentage of population with electricity access during 1990 to 2016 with a projection to 2030 (**a**) cities and (**b**) rural areas. Data provided by the World Bank [11].

Although a study shows [17] that by 2040, one billion people in Sub-Saharan Africa may get access to electricity, due to the population growth, this still will leave 530 million people without access to energy. Currently, there are joint efforts between the World Bank and ESMAP (Energy Sector Management Assistance Programme) to find a tool/method that facilities the way of measuring the electricity target in the SDG 7. This tool is very important, since current calculations are unable to take into account the multidimensional aspects of electricity access. These institutes also promote a MultiTier framework towards monitoring the progress for achieving the SEforAll and the SDG 7 goals.

4. Renewable Energy Increase in Developed Countries

Where in some parts of the world the access to electricity is still a major issue, in developed countries, the environmental input of the energy system gets more and more a core issue. For this, the European Union has created guidelines and laws to ensure that the member states commit in reaching the stated targets for energy saving and increased renewable energy share by 2020. This is related to the 20-20-20 goals, which are designed to have a 20% increase in energy efficiency, a 20% reduction of CO_2 emissions, and 20% of the energy from renewables by 2020. For the period after 2020, there are also road maps that specify the goals to be achieved before 2050, in which it is expected to have a fully renewable energy system [18].

Figures 3 and 4 show the share of renewable energy in 2004, 2016, and the target for 2020 in the different countries of the European Union [19]. The figures show that 14 countries of the European Union have already reached their target level for 2020. The furthest away from the 2020 target are: Ireland (7%), France (7%), Luxembourg (6%), the Netherlands (8%), United Kingdom (6%), Former Yugoslavia (10%), and Serbia (6%).

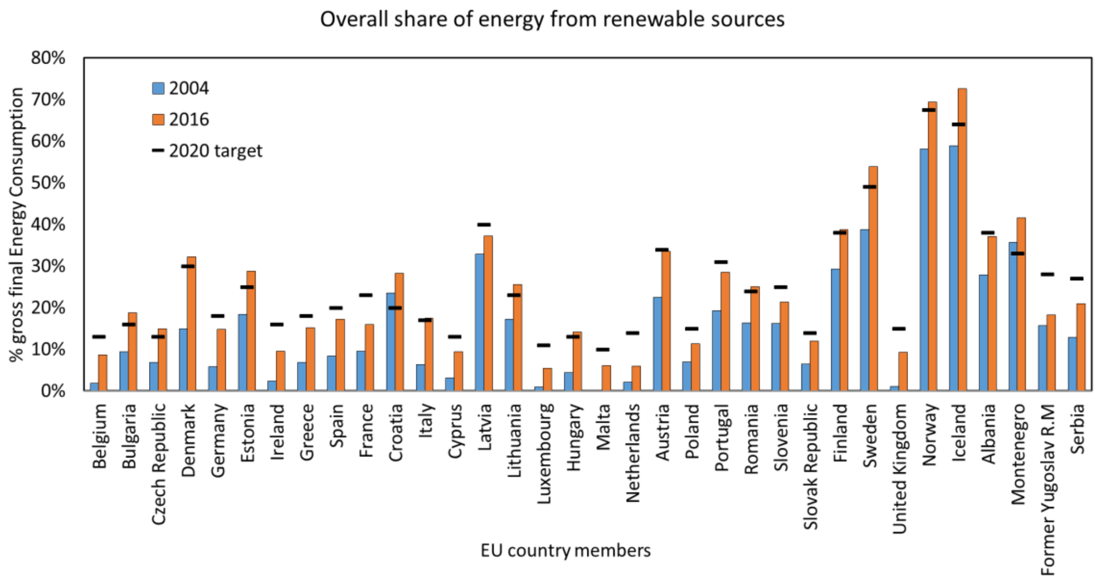

Figure 3. Overall share of energy from renewable sources in European countries, with the percentage of share in 2004 and 2016, and the target for 2020. Based on data provided by Eurostat [19].

Although there is a gap of 3% for European Countries to reach the 2020 renewable energy target (see Figure 4), the European Environment Agency has issued a report in 2015 called "Trends and Projections in Europe" in which it states that the EU is on track to reach the 2020 targets and there is a considerable improvement on reduction of Green House Gases (GHG) since 1990 [20]. The GHS emissions in Europe have been reduced since 1990 on approximately 19% in 2013–2014 and this trend is linked with the implementation of renewable energies. At the current trend, it is expected that the GHS reduction for the 2020 goals will be 24%. Moreover, if additional measures are implemented, the reduction may increase to 26% below the values of 1990. The EU has already created a set of climate and energy targets for 2030 that are in line with SDG 7. Furthermore, it is expected that the EU will reduce the use of fossil fuels and will increase the shares of renewable energy to at least 27%. Although many developed countries have already covered the energy reduction target of SDG 7, they still face problems. These problems are in general not based on limitations of or non-existing infrastructure (like is the case of countries in Africa), but follow from their increase in energy consumption and the too slow increase of energy from renewable sources.

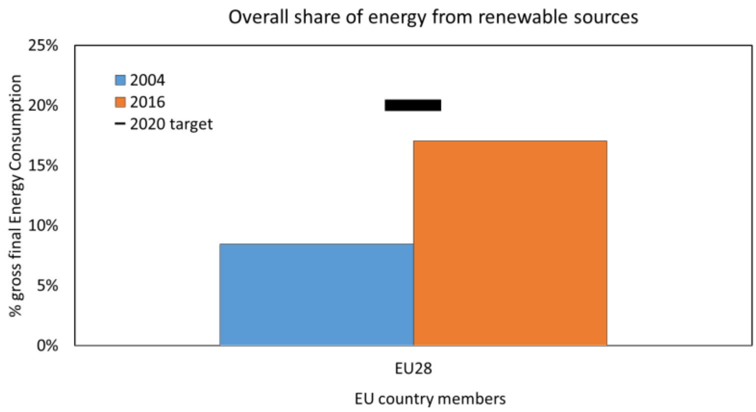

Figure 4. Overall share of energy from renewable sources in the overall European Union, with the percentage of share in 2004 and 2016 and the target for 2020. Based on data provided by Eurostat [19].

In the case of the EU, electricity coverage in cities and rural areas is at almost 100%. However, the stability of the grid tends to get affected by the large increase in energy consumption of houses, buildings, and industries [21]. Furthermore, the large demand of electricity and the need to reduce the use of fossil fuels has led to an increase in the installation of renewable energy on a small scale (e.g., solar PV at house level), but also on a large scale (e.g., PV and wind farms). This large-scale integration of renewables changes the flows in electricity grids and leads to extra uncertainty in the current electricity system. As the current electrical infrastructure was designed for a centralized power infrastructure in which only a small number of controllable energy sources on central locations were present, the increasing amount of decentralized renewable generation units affects the stability of the grid and its reliability [22]. These major concerns are:

- Excess of solar PV production in decentralized and centralized locations.
- Fluctuation of energy production coming from wind energy and solar farms.
- Increase in electricity demand due to replacement of gas-fired boilers for supplying the heating/cooling demand by heat pumps.
- Increase in electricity demand due to large increase in the penetration of electric vehicles (EV).

5. Off-grid Renewable Energy: Mini-grid/Micro-grid/Nano-grid Systems

In the previous sections, we have identified two major concerns for the electricity sector. Firstly, there is a need to provide worldwide access to electricity in line with the SDG 7, whereby the most problematic situation is observed in Sub-Saharan Africa, where access to electricity is as low as 32 % and current trends are not high enough to achieve the 2030 target. Secondly, in developed countries, the SDGs in general are focused on addressing climate change, protecting the environment, and provide stable electricity. The SDG 7 in particular encourages countries to create a more stable and reliable electricity grid based on renewable energies and to reduce use of fossil fuels.

To secure electricity access, there are two main paths that may be taken: First, grid base electrification, in which current electricity grids are extended if needed to urban and suburban areas, and secondly, off-grid electrification in rural areas on a micro-level, resulting in mini-grids and nano-grids at a house level. These two different strategies operate on a different scale and they give different perspectives on electricity access and services. Furthermore, they are both different in terms of investment and can serve different types of customers.

5.1. Grid Base Electrification

The conventional method to expand the electricity grid in cities has been similar in many countries. Table S1 shows the different types of approaches for extending the electricity grid and utilities. The electrification of an area usually comes with employment opportunities, improvement of communication, education, social services, and in general enriched quality of life. In the past decades, at least 1.7 billion people have been connected to national grids (mostly in urban areas). However, there are still major problems in connecting the electricity grid in rural areas, especially when the location and geography complicates the construction of the grid. For instance, in countries like Colombia, Chile, Mexico, Bangladesh, China, and Tanzania, the approach of grid expansion is an ongoing process, and large extensions of grid networks and power plants are under way [23,24]. One example of this is in Bangladesh, where energy optimization tools and planning have been researched in order to improve the electricity grid in Dhaka [25].

5.2. Off-grid Electricity

An alternative way to extend the electricity systems and increase electricity access is by employing off-grid electrification. Off-grid electricity means that smaller grids are set up that are not connected to the main grid. In principal, there are three approaches for off-grid electrification: mini-grid, micro-grid, and nano-grid systems. (See also Table S1).

1. A mini-grid operates usually with less than a 10 MW capacity installed, and it covers an area of around 50 km^2. These systems are usually used in communities and sometimes have a restricted connection to the national grid that is not very reliable. However, in many cases, they operate in isolated places, where a large demand has to be served during the day over the whole year.
2. A micro-grid distinguishes itself from a mini-grid mainly by its size. It operates with less than 100 kW of capacity, and it works at a low voltage level covering areas of around 3 km^2 to 8 km^2.
3. Nano-grids (e.g., an off-grid house) are usually used in remote communities. They may be implemented fast and they are used when a mini-grid or a micro-grid is still on the process to be implemented. Nano-grid systems are used mainly for individual houses, but they are possibly extended to approximately 1000 people. A new alternative for off-grid houses emerges, when these houses are still weakly connected to the main grid. In this case, houses (or buildings, industries) may be used in the grid as flexible assets, and they can be temporarily disconnected. For example, a house may be disconnected at times when the electricity consumption in the grid is too high; this approach may be used to reduce peaks in the main grid.

The mini- and micro-grids are usually powered by fossil fuels. Diesel generators are the typical option, nevertheless some new technologies are already tested and implemented, like fuel cells and renewable energy sources (e.g., solar PV, wind turbines etc.) combined with batteries. In the ideal case, an environmentally friendly mini/micro-grid consist of sources based on renewable power, storage, and a backup system. When the mini/micro-grids are designed and configured properly, they can be more efficient and cost-effective than a centralized grid. This is the reason diesel power and small hydro power mini-grids have been implemented in the past. An example of such a case is in Indonesia, where about 6000 people on islands use diesel generators and small hydro power plants to cover their electricity needs [26]. Nowadays, solar PV systems are starting to take over the market of diesel generators to reduce the consumption of diesel fuel, which is generally expensive in these areas [27]. Another case is in the Maldives, where a large part of the population use diesel-powered generators in a mini-grid structure to cover the needs of hotels and a few houses around the hotel [28]. Currently there is a transition in the Maldives towards 100% renewable energy solutions, and the first steps have been taken by making hybrid solar PV and diesel power plants [29].

In particular, when communities are far away from cities, a nano-grid solution can be used. In this case, a nano-grid system can be implemented faster and with less complexity than a mini/or micro-grid, which also have a connection to the main grid. In developing countries, small solar PV systems (called "nano" solar systems) are used, which produce a few watts of solar PV up to 1 kW and provide this electricity for lighting and charging mobile phones [30]. Furthermore, these systems are used to power small water pumps and other systems with low-power consumption. These nano-grid solutions are usually coupled with batteries, and they provide a simple electricity supply solution in situations where the grid is not present or not stable. Moreover, the cost of solar PV has been decreasing rapidly in recent years, which is due to the increase of the market volume, and is expected to keep on decreasing. The report on off-grid solar market trends [31] shows that solar PV products will grow from around $700 million in 2018 to around $2.4 billion in 2024. This report also estimates that about one out of three off-grid houses will use off-grid solar PV by 2020. Although the market for off-grid solutions is increasing considerably, there are still not enough incentives and strategies to speed up the implementation of off-grid systems in order to attain the 2030 SDGs goals for electricity access. For this, off-grid electrification has to overcome some important challenges, which are discussed in the next section.

6. Off-grid Electrification Challenges

Off-grid electrification is facing major challenges regarding implementation and contribution to electricity access and the goals for 2030. These challenges involve political, financial, technical, and regulatory issues. The World Bank and Energy for All indicated that the following challenges are of most importance. Please note that these challenges have been identified also by other researchers [32]:

- high initial investment,
- regulatory uncertainties,
- tariffs,
- stranded assets,
- supply and demand mismatch.

Off-grid electrification usually has a high initial investment. The initial high cost is due to the fact that these off-grid power plants are often designed for a higher power demand than needed for the short term. The power plant is expected to fulfill the requirements of a larger group of people in the future. However, if the location does not grow as expected, the system is underused and the revenue for the power plant may be never reached, creating problems for financing the system in the future.

Concerning regulation, usually investors need a regulatory system to reduce risks of their investments and to be able to provide services on a long-term basis. When an off-grid system is in place, it requires upfront legislation that specifies rules for tariffs, services, maintenance, and future plans for grid implementation. Furthermore, in India, there are, for example, efforts to create a more stable mini-grid system in which users are willing to pay for this stability, and the government is willing to provide services for both the electrical grid and the off-grid power system [33]. Tariffs in off-grid electrification are usually higher than in the regularly connected electricity grid, especially for those consuming small amounts of electricity. Furthermore, when there is no subsidy for the off-grid electrification system, the electricity tariff has to fully recover the investment cost of the power system.

Another problem for off-grid electrification is when technologies become obsolete or when they do not work properly during their life span. This is usually known as stranded assets. In perspective, when the main grid reaches areas where off-grid electrification is present, the off-grid assets may not be used anymore, and investments may not be recovered. For this reason, it is necessary to create a protection for these assets with legislation to recover the investments, even if a grid connection is established in the future.

A challenge for off-grid electricity is the supply and demand mismatch, in particular due to the fluctuations of renewable energies from solar or wind energies. When powering a mini/micro or nano-grid with renewable energy, it will have an underuse of the resources for some parts of the year. This is the case, because to provide electricity during months of low energy production (e.g., in winter), the system needs to be oversized, and this creates an increase in costs. Nowadays, diesel generators can supply the electricity needed when there is a low production of renewable electricity; however, this also creates extra cost for the power system. Likewise, batteries can be used, but they also have a high cost and do not have the capacity to cover seasonable effects. However, in some cases, some amount of demand can be optimized, e.g., using decentralized energy management to use appliances only when production is high, thus reducing the need for backup power [34].

To achieve a better and cost-effective implementation of mini/micro- and nano grids, schemes for off-grid electrification have to be evaluated in more detail. The transition to an electricity grid with massive contributions from renewable energies can only be achieved if corresponding measures are taken into account. Furthermore, off-grid electricity may have a better implementation if actions are taken towards legislation, regulation, technology, and financial issues. A few such measures are shown in more detail in Figure S1.

Taking into account the mentioned challenges, it has been observed that off-grid electrification requires strategies, policies, innovative technologies, and adaptation. Furthermore, mini/micro and nano-grids are designed for specific populations and electricity demands (see Table S1). In Section 7, we focus on stand-alone/nano-grid houses, since research at University of Twente and the literature mentioned in the previous sections have shown that nano-grid houses maybe an important asset for the electricity systems of the future. However, creating a 100% stand-alone house is still a task that to our knowledge has not been fully used. The stand-alone house is economically interesting if the house has a supply of electricity all year round without shortage, with an affordable technology that is possibly able to compete with a grid-connected situation.

7. Example of a Nano-grid System

As mentioned above, nano-grids or islanded power grids are becoming an important asset that may increase electricity access in rural areas. Such an off-grid system uses various types of renewable electricity sources. They are connected with batteries and a backup power system to avoid power outage. Figure 5 illustrates a common configuration for an islanded off-grid house. It takes into account the need for electricity for heating, electrical appliances, water production, and waste water treatment. This nanogrid or standalone house has the following main components:

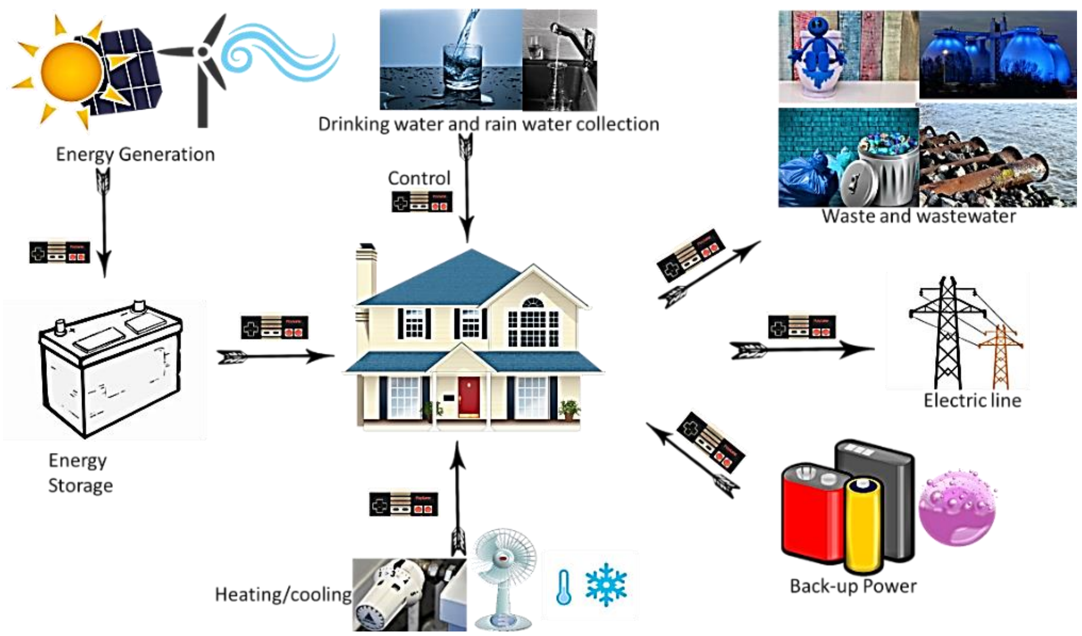

Figure 5. Setup for a nano-grid house.

1. Generation of electricity: solar PV or wind turbines.
2. Energy Storage: usually Lead Acid, Li-ion, or NiMH batteries for standalone houses.
3. Back up units: a generator or a fuel cell, a micro CHP based on renewable sources (e.g., biogas or wood pellets) or small biodiesel plants.

4. A connection to an electric grid line, if present, which is only included for taking up electricity surplus.
5. Devices in a house that consume the major part of the electricity; in our case, standard appliances, a water cleaning unit, a waste and wastewater treatment plant, and heating and cooling units.

The combination of these different-generation technologies provide all the electricity that is needed for a house to function daily all year around. However, in practice, a cost-effective and efficient technological solution that can be embedded in different scenarios is still not quite available. There are only a few cases of islanded houses in the world, whereby these approaches are related to small off-grid houses or compact livings, such as in South Wales [35] and Italy [36]. These approaches show that current technologies are in principle able to provide the electricity required for an off-grid house; however, an all-year cost-effective supply of electricity for all the energy needed in a house still is a major challenge.

8. A Case Study for an Off-grid House in the Netherlands

In this section, we present a case study for an off-grid house. The goal of this study was to show that it is technically feasible to develop an off-grid house. The economic aspects of off-grid houses are beyond the scope of this paper. Figure 6 shows the setup of an islanded off-grid house using new sustainable technologies developed in the Netherlands. In general, the setup uses various technologies to generate the electricity needed for a house, and it is designed to also supply electricity to a decentralized wastewater treatment plant (DWWTP). To achieve this, solar PV is used coupled with a battery.

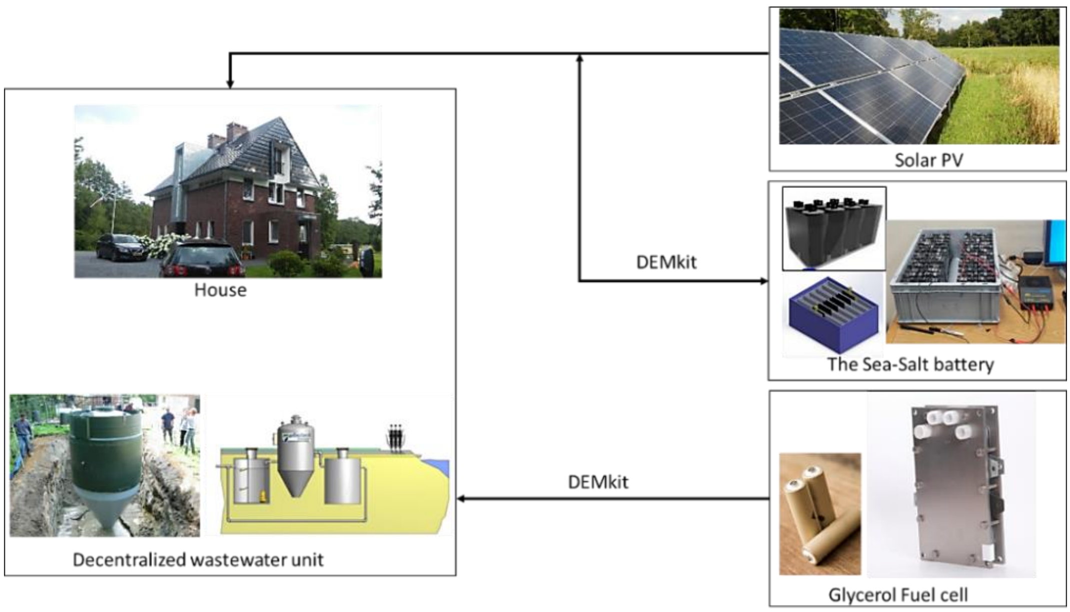

Figure 6. Prototype set up for an islanded off-grid house.

During the day, solar PV provides electricity and during the night or during low solar irradiation, the battery is used as main electricity provider. Furthermore, a fuel cell is used as a backup power unit. The fuel cell is only used when solar PV and the battery are not capable of providing the electricity demand. In the following, a more detailed description of the technologies for this setup of a stand-alone house is given:

- Solar PV: Various types of commercial solar photovoltaic panels may be used for off-grid houses. Data of solar PV electricity output can be found in different sources; see Pecan Street in the USA [37], or data from the electricity company Alliander in the Netherlands [38], or data collected from measurements of electricity production/consumption loggers [39].

- The Sea-Salt Battery: This battery is a new energy storage system based on carbon graphite and with an electrolyte made of salts and additives. The battery is currently under testing in the Netherlands, USA, Belgium, and Israel, and it is expected that the battery will be on the market by 2022 [40,41]. This battery has been previously used in research by our group at University of Twente for use in smart grids [41,42]. In terms of cost, the battery is made of abundantly available materials, and the expected future cost by 2025 is 100–300 Euro/kWh. The producer claims that the battery is capable of 10000 electricity cycles with low signs of degradation.
- The Glycerol Fuel Cell: The glycerol fuel cell is an electrochemical system that is capable of transforming glycerol directly into electricity using a gold base catalyst. Glycerol is a by-product (waste product) of bio-diesel production. This technology has been investigated in our research group [43]. Currently, the system is under development and it is expected to be on the market by 2025.
- The DEMkit (version 2018, University of Twente, Enschede, the Netherlands): The simulation package DEMkit is a tool for decentralized energy management developed at the University of Twente [44,45]. DEMKit makes use of discrete time-series dynamic simulations, using a bottom-up modelling approach. A library with device, grid and control components is available in the tool. Generic device components are available that model the behaviour of a device and its operation constraints, such as the battery capacity. Attached control algorithms can be used to optimize the operation of devices taking into account the given constraints.

The given devices can be connected to a physical grid model, such that it is possible to evaluate the effects of control actions on the delivered power and power quality (The sea-salt battery and the glycerol fuel cell are systems created by the company Dr Ten BV [46] as part of their ongoing research on sustainable energy storage technologies).

Using DEMkit the performance of an off-grid house equipped with solar PV, a sea-salt battery and a glycerol fuel cell was evaluated. Furthermore, the simulations could be used to determine suitable parameters of the appliances (e.g., size of PV panels, storage capacity of the batteries and fuel cell), such that the house may be used off-grid over a complete year.

The electricity consumption used for this simulation (see red line in Figure 7) has been recorded in a house consisting of 5 residents. The house is equipped with regular appliances (fridge, TVs, washing, and drying machines), and also equipped with a hybrid vehicle that is charged regularly.

The goal of the simulations with DEMkit was to investigate whether or not the house load could be covered by solar PV, the battery, and the backup unit. For the storage, the sea-salt battery has been used as an ideal device, meaning that the battery may be discharged for 100%. In contrast to Li-ion batteries, a sea-salt battery can withstand 100% discharge without damage. The glycerol fuel cell was considered as a back-up unit, only to be used when the sea-salt battery and the solar PV are not capable of providing the required electricity for the house. In DEMkit, the glycerol fuel cell is programmed to start when the battery is below 20% capacity.

Preliminary results using DEMkit for an off-grid house in the Netherlands using solar PV, a sea-salt battery, and a glycerol fuel cell, with energy profiles of one week during June 2016 are presented in Figure 7. The house load (red line) and the solar PV profiles (yellow line) were recorded in a house in the Netherlands (the data has been provided by the company Alliander) [38].

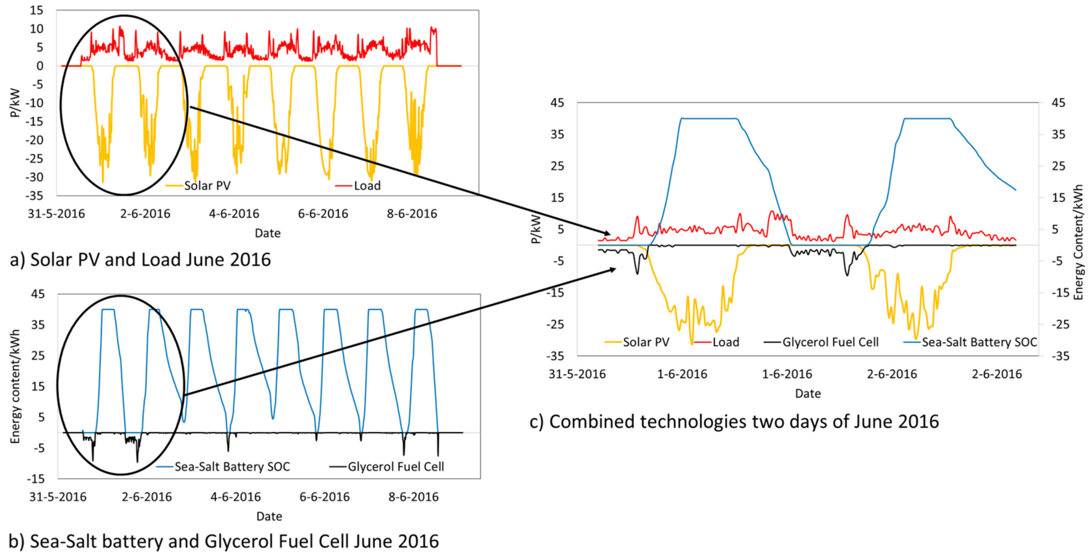

Figure 7. DEMkit results of an off-grid house in the Netherlands with Solar PV, Sea-Salt battery and a Glycerol Fuel Cell during one week of summer 2016 showing (**a**) Solar PV and Load, (**b**) Sea-Salt battery SoC and Glycerol Fuel cell power and (**c**) a zoom in on June 1 and 2 2016 with Solar PV, Load, Sea-Salt battery and Glycerol Fuel Cell.

Discussion of the Results

Figure 7a shows the data of electricity load and solar PV production during the first week of June 2016. Figure 7b shows the electricity content of the simulated sea-salt battery and the production of the backup glycerol fuel cell during the first week of June 2016, and Figure 7c shows the zoom in of the compiled data of the house load, solar PV, the sea-salt battery and the glycerol fuel cell in the first two days of June 2016. It was observed in detail that the overall profile of solar PV was constant throughout the days, and a maximum electricity production of 30 kW was observed. On the other hand, the house load showed a maximum value of 10 kW during the first week of June 2016 (see Figure 7a). In Figure 7b, it was observed that the sea-salt battery stored the surplus of electricity that was provided from the solar PV during the day. Furthermore, the sea-salt battery is discharged typically during the evening and night (the modelled battery has a size of 45 kWh). Moreover, during the night, it was observed that the sea-salt battery did not always cover the required house load. In such situations, the glycerol fuel cell of 11 kW (black line) covered this demand and was active until the solar PV covered the demand of the house on the next day. In Figure 7c, a more clear detail view of the interaction of the solar PV, the sea-salt battery, and the glycerol fuel cell is given for the first two days of June 2016.

Figure 8a shows the data of electricity load and solar PV production during a winter week in January 2016, and Figure 8b shows the corresponding electricity content of the simulated sea-salt battery with the backup glycerol fuel cell during the same week of January 2016. Furthermore, Figure 8c shows the zoom in of the compiled data of the house load, solar PV, sea-salt battery, and the glycerol fuel cell during two days of the same week. In detail, it was observed that overall, the profile of solar PV stayed constant over this week and the maximum electricity production was of 30 kW.

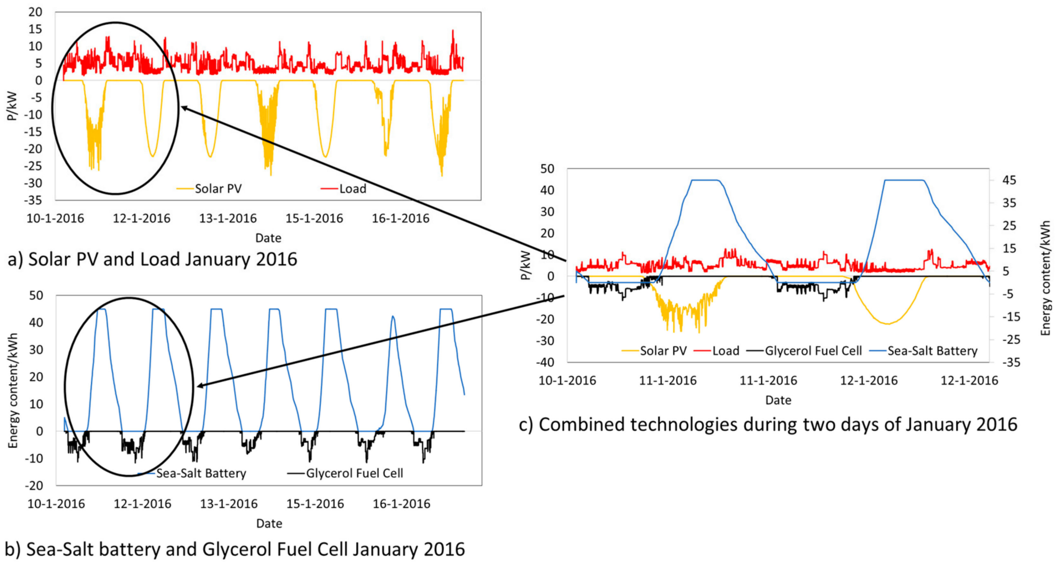

Figure 8. DEMkit results of an off-grid house in the Netherlands with Solar PV, sea-salt battery and a glycerol fuel cell during one week of winter 2016 showing (**a**) Solar PV and Load, (**b**) Sea-Salt battery and glycerol fuel cell cell and (**c**) a zoom in on January 11 and 12 2016 with Solar PV, Load, Sea-Salt battery and glycerol fuel cell.

On the other hand, the house load shows a maximum value of 15 kW during the week of January 2016 (see Figure 7a), which is higher than the load in the week of June 2016 (10 kW). In Figure 8b, it was observed that the sea-salt battery stored the surplus of electricity that was provided from the solar PV during the day. Furthermore, the sea-salt battery was typically discharged during the evening and night, and this occurred during longer periods of time than in the summer (the modelled battery has a size of 45 kWh). Moreover, during the winter night, it was observed that the sea-salt battery did not always cover the required house load. In such situations, a glycerol fuel cell of 16 kW (black line) covered this demand and was active until solar PV covered the demand of the house on the next day. In Figure 8c, a clearer detailed view of the interaction of the solar PV, sea-salt battery, and glycerol fuel cell is given for the 10th to the 12th of January 2016.

To summarize, it was observed that a house in the presented scenario in the Netherlands was capable of being off-grid by having a solar PV of 30 kW with a sea-salt battery of 45 kWh and a glycerol fuel cell of 11 kWh during the aforementioned week in June 2016. In the case of the tested week in winter, it was observed that the size of the glycerol fuel cell had to increase to 15 kW but the solar PV and the sea-salt battery could work with the same size in the summer and in the winter.

The above results are supported by the simulation created for longer periods of time, as shown in Figure 9. The simulation is presented over a 7 months period, from June to December 2016. It was observed in Figure 9 that the results support the simulation performed for the weeks of January and June (see Figures 7 and 8). Also, Figure 9 shows the same behavior as the simulation performed for the weeks in Figures 7 and 8. However, notice that during the months of November and December, the glycerol fuel cell is used more often than during the more sunny periods. Nevertheless, this could have been expected, based on the weather differences.

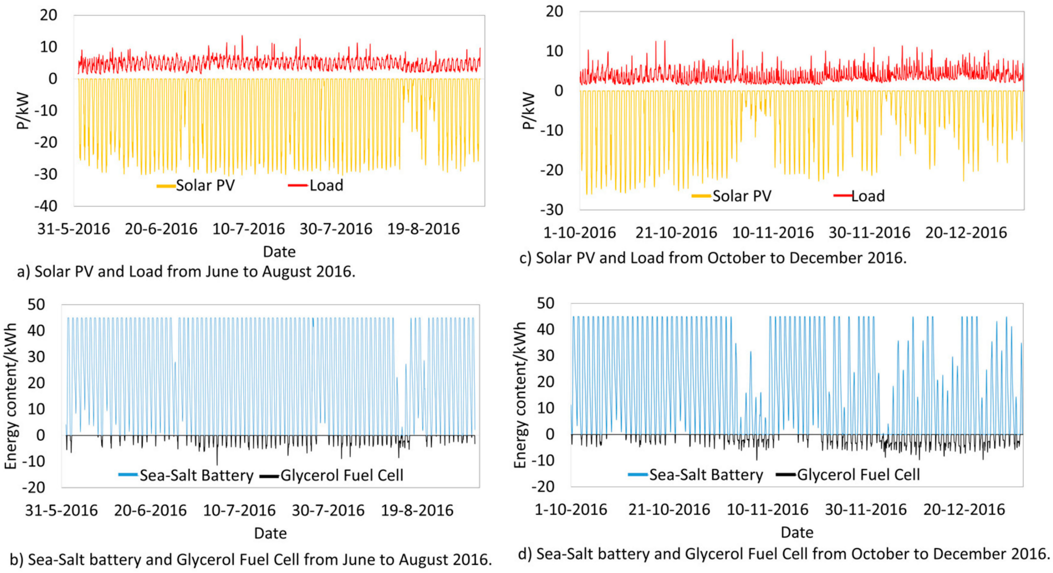

Figure 9. DEMkit results of an off-grid house in the Netherlands with hourly data with Solar PV, sea-salt battery and a glycerol fuel cell during the months of June to December 2016 showing (**a**) Solar PV and Load from June to August 2016, (**b**) Sea-salt battery SoC and glycerol fuel cell power from June to August 2016, (**c**) Solar PV and Load from October to December 2016, (**d**) Sea-salt battery SoC and glycerol fuel cell power from October to December 2016.

9. Conclusions

Off-grid houses may be an important asset for the electrical grid, on the one hand, to increase the electricity access in the world and, on the other hand, to allow a better integration of renewable energy sources in the energy system. Initiatives to improve the access to electricity are plenty, but the rate of implementation of practical solutions is far below the UN Sustainable Development Goal 7 Energy (SDG 7) for 2030. It has been observed that this problem is most apparent in Sub-Saharan Africa, where the current trends of electricity access calculated by the World Bank indicate that they will not be able to achieve the SDG 7 by 2030. On the other hand, the current worldwide introduction of renewable energy at the house level leads to an unbalance of electricity in terms of generation consumption, which in the future may cause a shortage of electricity in some periods of the year. Remarkably, the implementation of renewable energy generation using the bottom-up approach of off-grid houses is happening at a faster rate in developing countries than in developed countries.

In this paper, it was shown that for a case study in the Netherlands, the bottom-up approach of off-grid houses may have the potential to create a possibly more effective solution in the future for increasing renewable generation. The approach integrates the use of a new battery technology (sea-salt battery), a fuel cell (glycerol fuel cell), and a smart decentralized energy management system (DEMKit). It was observed that a house in the Netherlands was able to be off-grid, by having a solar PV of 30 kW with a sea-salt battery of 45 kWh and a glycerol fuel cell of 15 kWh working all year round.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/12/10/2033/s1, Figure S1: Measures to facilitate the implementation of off-grid electricity, adapted from Energy Access Report and Clean Energy Ministerial 2013 [1,6]. Table S1: Methods for expanding electricity and utilities, based on [1].

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