MSc Program
Renewable Energy Systems

Lighting off-grid communities using E-waste and glass

A Master's Thesis submitted for the degree of
"Master of Science"

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15th October 2017, Vienna

Affidavit

I, **ANGELA LAVERDE**, hereby declare

1. that I am the sole author of the present Master Thesis, "Lighting off-grid communities using E-waste and glass",
   92 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

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Date Signature

ABSTRACT

The work for the execution of this thesis was guided by the motivation to understand the magnitude of the problem and the implications for people living in developing countries, who don't enjoy basic access to energy services.

Bringing together the knowledge acquired in Renewable Energy Systems and the core competencies in Electronics Engineering, it was an understandable choice to investigate the possibility to design an electronic device, which would be able to respond to a basic need, lighting a bulb, in a practical, economical and eco-friendly way.

The sense of one purpose should not be measured only by the results, as it is not because the results are not as hoped for, that the attempt was not worth the effort, as long as the underlying assumptions were sensible and testable.

In the present case, in consideration of the properties of photosensitive semiconductor pn-junction, it was assumed that LEDs – as semiconductor light detectors – could generate enough power for lighting a light bulb. The series of tests performed by exposing various LEDs in different configurations to the sunlight, show that the current output is not sufficient to light a bulb but enough to trigger a circuit and therefore is not fit for the original purpose (providing light to left-aside off grid communities) but could still be developed further to give a second life to electronic waste.

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1 INTRODUCTION

1.1 GENERAL OVERVIEW OF THE CONTEXT

According to the Global Energy Assessment (coordinated by the International Institute for Applied Systems Analysis [IIASA]), around one and a half billion people worldwide still live without any electricity and more that three billion depend on solid fuels (wood, charcoal, coal…) to improve their living conditions (GEA, 2012).

Access to electricity should be a fundamental right knowing that it fulfills the basic human needs, and allows and improves social development, economy, health, education and nutrition.

The populations that are suffering the most are the one living in communities in rural areas and urban slams in developing countries, where no infrastructure for access to electricity has been installed yet. The communities are therefore 100% depended on solid fuels for cooking, warming and lighting their homes.

The following Map in Figure 1 below shows an overview of worldwide electricity access and the countries most affected by the lack of access. Countries in Latin America, Africa and Asia are the ones with less access to electricity, as it is related to poverty, demography and geography.

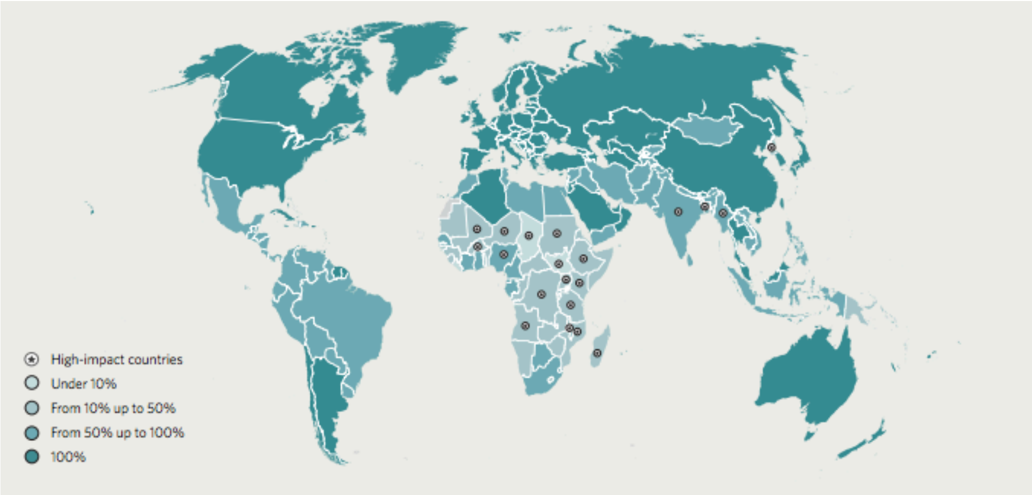


Fig. 1: Global electricity access in 2014. Source: SE4ALL (2017)

Going into further detail, the next map (Figure 2 below) shows the 20 most affected countries in terms of lack of electrification as well as the number of inhabitants in those countries who lack access to electricity. Those countries are mainly situated in South Saharan Africa and Asia: The rural areas of India are the most affected followed by Nigeria.

In the past years, Asia has made a significant leap forward, expanding access to electricity at a rate higher than the annual population growth rate. In particular solar photovoltaic systems played an important role for rural areas without connection to the electrical grid system. (SE4ALL, 2017)

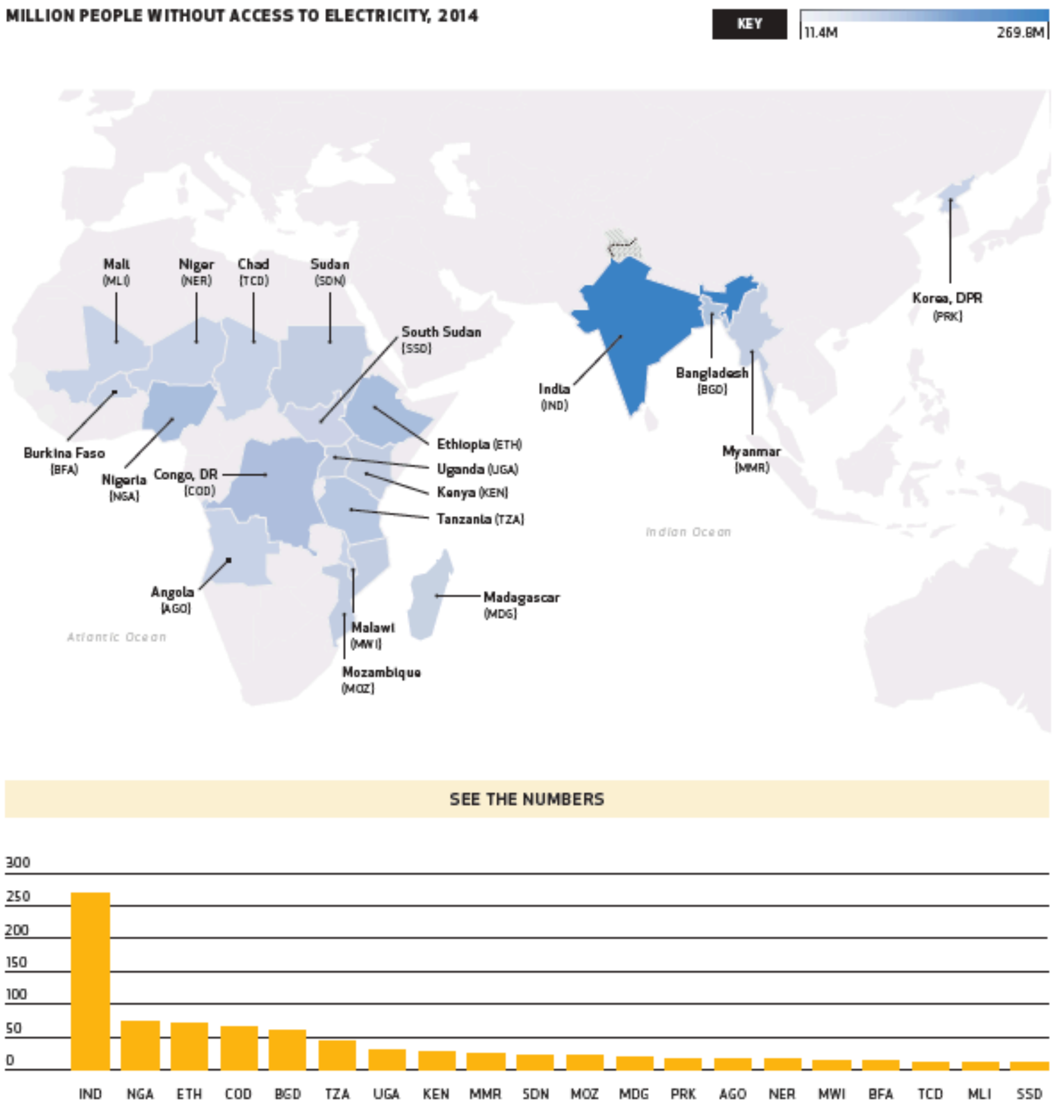


Fig. 2: Million people without access to electricity, 2014. Source: SE4ALL (2017)

Electricity is an important tool for development. The use of a mobile phone, Internet access, lighting, which are considered basic or ‘normal’ needs for many people around the world are unfortunately still unreachable for many people in developing countries. Improving the access to electricity can therefore have a big impact in the daily lives of this population and it can foster economic development.

Poverty means not only to deprivation of income, but also a lack of access to resources and assets, social networks, voice and power (UNDP, 2010) as well as basic services including energy. In poverty, injustice strikes two-fold: people who suffer from not having modern access to energy, end up paying more for the use of traditional means, than they would pay if they had access to electricity, although depending on the countries' energy system and regulatory framework. Moreover, the areas that suffer the most from lack of access to energy are also most vulnerable to climate change, because the populations are directly dependent on their local ecosystems to cater for their energy needs. The Intergovernmental Panel on Climate Change described Africa, the world's poorest region, as "the continent most vulnerable to the impacts of projected change because widespread poverty limits adaptation capabilities" (IPCC, 2007). The United Nations Secretary-General's Advisory Group on Energy and Climate Change (AGECC, 2010) has set new objectives as it is aiming at ensuring universal energy access by 2030 (full grid power, all day, every day). A short look of the historical progress of the electrification can give a better perspective of this goal.

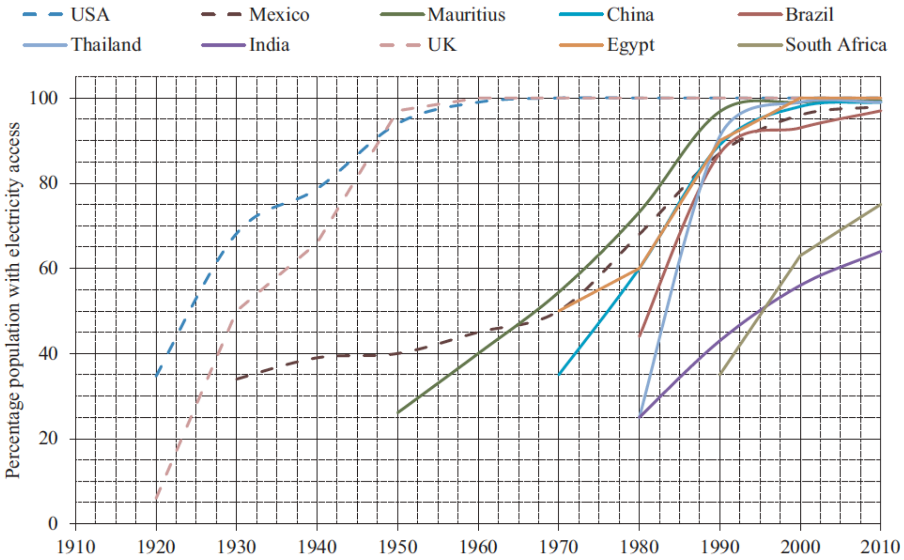


Fig. 3: Historical progress of electrification. Source: GEA (2012)

It was in the United Kingdom that electricity was first commercially supplied to the public as early as in the mid-19th century. It then spread rapidly throughout Europe and the United States (Smil, 2005). In the 20th century electricity access to the population was a priority for the governments because it was a prerequisite for modernization and development of the nations. Not all countries of the world achieved the same degree of electrification, mainly for political and financial limitations. According to figure 3, UK and USA were the first to achieve the goal of 100% electrification after 40 years of sustained efforts. It took 90 years for Mexico, 20 years for Thailand 20. However, in a stark contrast with these achievements, there are still many households suffering lack access to electricity in Latin America, Africa and Asia (Figure 4).

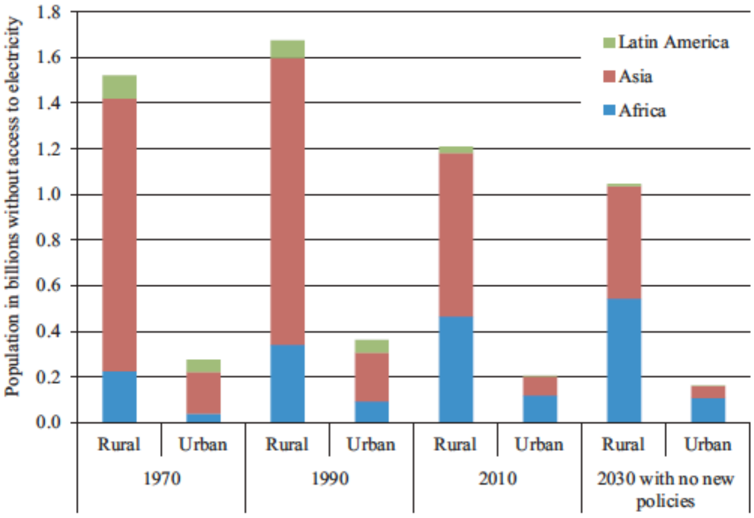


Fig. 4: Population without access to electricity in Latin America, Asia and Africa. Source: GEA (2012)

Figure 4 illustrates in a closer view, the history of electrification of Asia, Latin America and Africa. Due to rapid population growth, between 1970 and 1990 the population without access to electricity increased. Globally, between 1990 to 2010, the degree of access to electricity increased because of electrification efforts from major countries like China and some others in Latin America. But, according to the Global Energy Assessment (GEA 2012), in the year 2030 if no additional policy measures are taken, around 30 to 40% of the rural populations in Asia and South Saharan Africa will still remain un-electrified.

This historical perspective shows that with judicious state intervention, policies to set up attractive frameworks for investors as well as with sustained and shared commitment; access to electricity for all is an achievable goal. However, at the time being the conditions are not met. Energy providers tend naturally to invest in projects that generate enough income and profit: without economic development in many rural and urban areas of lagging developing countries, it is unlikely to attract them to those markets. Therefore the implementation of new energy programs is essential for reaching the new goal “Electricity for all in 2030”, which appears very ambitious today, but only fair.

International institutions in association with other entities (public or private) have developed and implemented programs for helping tackle the lack of access to electricity. There are many challenges: a major obstacle for the projects financed through these programs is often the distance between the source of supply of energy and the rural areas needing access. Another limitation is the affordability of the systems deployed for many households, due to their low income and lack of accessible ways to pay the electricity.

As an example, Lighting Global is a World Bank Group’s platform to support sustainable growth of the international off-grid solar market. This program supports local energy market development by working with private companies to lower the risks when venturing themselves as first movers into the market. In parallel to mobilizing private sector investment, it provides support through market intelligence, quality assurance, business support services and consumer education (Lighting Global, 2016).

A declination of this program is the World Bank Group’s project Lighting Africa, which through off-grid solar products has already given the possibility to more than 20.5 million people in Africa to meet their basic electricity needs (charging a mobile phone and lighting). In the same way, Lighting Asia is an IFC (International Financial Corporation) market transformation program, working to increase access to clean energy services in the rural areas of Bangladesh, India and Pakistan. The Lighting Asia program works with the private sector and development organizations to catalyze markets for modern, solar lighting products and systems (Lighting Asia, 2015).

These are examples of programs, which are essential to kick-start the sector and create favorable conditions, but the long-term success eventually depends on the implementation of adapted business model apt to attract finance. In many countries, the system called Pay As You Go (PAYG) has established itself like a favorite: it allows households to pay a small amount each month making the access to electricity more affordable. It also gives the possibility to buy and own system or use leasing. But there are drawbacks too: the problem is that could be a trap for debt. As solar investor Jamie Harztell was quoted in an article from the Guardian (UK):

“The boom in pay-as-you-go household solar in East Africa is very exciting. But it is all based on credit, and the companies have a view to selling other products like TVs. How big is the risk that boom will turn to bust and push the poorest of the poor into unplayable debt?” (Harztell, 2016)

1.2 MOTIVATION

The picture described in the previous section shows that in spite of the many promising developments and initiatives launched, people will still be left aside, who cannot afford to pay the price of electricity for having one reliable lighting spot. To find a practical, economical and clean solution for these households is the central motivation for this Master thesis.

Indeed, the motivation of this research work is to develop a sustainable solution for access to electricity at the local level, for households living in off-grid communities to meet the basic energy need of lighting a bulb. These homes often don’t have power, not even during the day for one light bulb (to lighten the rooms inside which are often in the dark, because of how houses are built). The main issue is that they cannot afford to pay for the leasing of solar panels.

The objective of this research is to investigate the possibility based on the principle of the photosensitive p-n junction to generate enough electricity from electronic waste (LEDs) and glass to light a bulb. If this turns out to be technically and economically feasible, this device could be used to bring lighting to off-grid communities, improving their quality of life.

One important aspect about the opportunity to use electronic waste is that over time, e-waste has become a global environmental and health issue. For this reason, one of the objectives of this Master Thesis was to develop a device encouraging to recycle electronic waste. However, the opportunity to use electronic waste is limited by the fact that it subject to mishandling and illegal traffic, leading to pollution and consequently safety and health issues. For this reason, stringent constraints in terms of quality assurance standards have been put in place by international organizations providing finance (e.g. Lighting Global initiative led by World Bank Group) to protect population and environment. Therefore, it is important to make sure that the e-waste used for the device would be obtained through accredited processes and suppliers.

1.3 METHODOLOGICAL APPROACH

The thesis is divided in 2 parts: The first part encompasses Chapter 2 and 3, while the second part is comprised of Chapter 3 and 4.

The aim of the first part is to understand the context in developing countries in terms of energy access as well as the conditions for the deployment of off-grid energy systems, in order to identify the constraints and the possibilities opened to alternative ways of providing energy services: In the present case to provide lighting. The information used for the description of the background for the motivation of the thesis, was sourced from reports produced by the mayor institutions active in the field of energy and development (World Bank, Se4All, UNDP, IIASA…), highlighting the lack of access to basic lighting for many people in spite of the many initiatives. It confirmed the opportunity to look for alternative ways to provide lighting, which is the purpose of the second part.

The second part consists in applied research work, based on investigation, which regards to underlying scientific theories and developments. The guiding principle of the applied research work was to find out which semiconductor pn junction in reaction with outdoor sunlight would produce the highest yield in current.
There are two possible types of sunlight conversion into electricity, when sunlight waves strike a pn-junction: one is the photosensitive effect and the other is thermoelectric effect, depending on the characteristics of the material exposed.

The thermoelectric reaction is known as Seebeck effect: it is a phenomenon experienced when two different semiconductors or electrical conductors are connected, forming a pn- junction, with a difference in temperature between each end of the junction: an electrical potential is then induced by the flow of electrons from the higher temperature side to the lower temperature side. This property of the materials is called Seebeck coefficient, as it varies in function of the materials. Thomas Seebeck discovered this effect of the semiconductor and electrical

conductors in the year 1821. It is one of the basic principles of the thermocouple. For the purpose of this work, many tests were carried out with different P type and N type semiconductor metals, facing the sunlight to heat the junctions. The PN junctions fabricated were on copper as P type and iron as N type, copper as P type and aluminum as N type, and copper oxide as P type and copper oxide as N type, all in function of the Seebeck coefficient of the materials.
Many tests were performed, exposing the P junction to the sunlight to increase its temperature, but the results were not as expected as the temperature difference between the p and n junction metals was not enough to generate sufficient current and voltage for the objective of this work.

Based on the above test results, it was decided to focus the applied research work on the LEDs, given the proven capability of LEDs as photosensitive semiconductor: indeed, LEDs, used as light detectors, present the necessary properties to generate current. Due to the advantages of their small size, long lifetime, high stability, low heat production, low power consumption and its availability as e-waste, they appear to be well suited for the central purpose of the present research work. The question is whether it is possible to develop a device, which generates enough electricity to lighten a bulb.

The guiding principle of the applied research work was to find out which semiconductor P-N junction composition, in reaction with outdoor sunlight, would produce the highest yield in current.

The approach used to optimize the results was through trials, whereby a series of tests were carried out, to determine the correct LED type to be used for the successful development of the device.

As such, different kinds of LEDs in shape, composition and size were exposed to outdoor sunlight: Under clear sky conditions, regular measures were taken to find out the maximum current output. When the current output reached its peak the voltage output of the LED was also measured. For the purpose of this work, the current output matters over the voltage output, because voltage can easily be amplified (for instance with a voltage multiplier, which is a special type of diode rectifier circuit), while current needs an extra source of energy to increase the output.
It shall be noted that for the purpose of the present work brand-new LEDs were used, instead of e-waste LEDs, but it is assumed (although ideally it should be

verified) that the properties don't alter over time.

The methodical approach consisted in identifying the main levers (size, photodiode response to light intensity, type and scaling) that would influence the output (generation of current). Each of the levers was actioned independently, step by step:

- The first step of the applied research process was to determine whether the size of the LED would influence the output generated in terms of voltage and current.

- The second step was to measure the photodiode response to the exposure to the sunlight (light intensity), depending on the type (composition, size) of the semiconductor P-N junction (detecting either yellow, blue, green, red or infrared wavelength light).

For the first and second step, it was preceded by elimination. The third and fourth steps outlined below were undertaken as an alternative to the single P-N junction standard LED which was used in step one and two.

- As such, the third step was to determine the photodiode response in function of the type of the LED to the exposure to the sunlight (light intensity), distinguishing between LEDs with one single P-N junction and LEDs with multiple P-N junctions integrated in surface mounted modules.

- The fourth step was to check whether scaling up the circuit by connecting LEDs in series or parallel would yield better results in terms of voltage and current.

Note that the duration of the exposure to sunlight was not a determining parameter, as LED’s react promptly to sunlight and reach rapidly the maximum potential of their photosensitive response. The current was measured simultaneously with the voltage.

2 THE CHALLENGE OF ACCESS TO CLEAN ENERGY AS A CONDITION FOR SUSTAINABLE DEVELOPMENT

2.1 THE MEANING OF ACCESS TO ENERGY

According to UN's Energy Sector Management Assistance Program, there are two aspects to access to energy (ESMAP, 2015):

- Access to energy services which is defined as the ability of an end user to utilize energy services (such as lighting, phone charging, cooking, air circulation, refrigeration, air conditioning, heating, etc.) that require an energy appliance and suitable energy supply.

- Access to energy supply which is defined as the ability of an end user to utilize an energy supply that can be used for desired energy services.

This means that energy supplied which does not fulfill certain requisites necessary to ensure the provision of energy services cannot be considered as 'accessible' energy.

As stated in (ESMAP, 2015) report, access to energy used to mean strictly household access to electricity, which used to take different forms: a household electricity connection, an electric pole in the village, or an electric bulb in the house. However, it does not account for the quantity and quality of electricity provided, or for the limitations of the supply, which may constrain the energy service provided. For example, in case of a household energy connection, connected households may receive electricity at low voltage, for limited hours, but during hours of the day or even night when it is not needed in priority, and with poor reliability: of course, this would limit the range of possible uses. Neither does it address the question of affordability of energy.

Therefore, to get a full understanding of the meaning of energy access, following concepts need to be taken into account, as outlined by ESMAP:

- Access to energy supply, access to energy services, and actual use of energy need to be distinguished. Full access is often the term of an incremental process (ESMAP, 2015) or achieved through the provision of multiple layers of specific energy solutions.
- Throughout its history, the primary motivation driving the expansion of energy access has always been socio-economic development: therefore energy access must have a number of attributes in terms of quantity and quality of the supply, availability, reliability, convenience, affordability and safety.
- Access to energy does entail different meanings depending on the level where it is needed, whether at household level, for productive and commercial purposes, or at the level of the community. At the household level, access to energy encompasses electricity, e.g. for lighting, as well as cooking and heating solutions.
- The energy provided through access should have all the attributes necessary for use in the applications that the user needs or wants.
- The usability of energy for desired services depends on the attributes of the supply, like capacity (adequacy), availability, reliability, affordability, quality, legality, health impact, safety, and convenience.

2.2 ATTRIBUTES OF ENERGY SUPPLY

As inferred from the above, access to energy is conditioned to the potential of the energy supplied, to respond to the needs when required by the users, by powering applications that a user needs (or wants – depending on the degree of social and economic development). This means that the energy provided should have the attributes required for powering these applications, otherwise the supply may be considered deficient or even useless. As an example, an electricity connection in a local health clinic in a remote village using low-voltage (LV) lines may not be able to provide adequate quality of supply for running x-ray machines, therefore rendering the acquisition of the x-ray machines and the provision of the health service dependent thereupon useless. The other way round, a solar home system may no suffice to power an air conditioner, but may be a reliable source of supply for powering light bulbs for a few hours a day.

Following ESMAP, the attributes of energy supply are the characteristics that determine the ability of the users of the energy supplied, to convert it into the required energy services, which in turn contribute to fulfill predetermined needs (reading, cooking, etc…). The attributes of energy include capacity, availability, reliability, affordability, quality, health impact, safety, legality, and convenience. The attributes required for energy supply change with the increase of income and the expected use of the supply, as the needs become more sophisticated.

ESMAP defines the attributes of energy supply as follows:

- Capacity: quantity of energy available compared with service requirements,
- Availability: timing and duration of energy supply.
- Reliability: frequency and length of interruptions to supply.
- Quality: voltage and frequency fluctuations.
- Health impact: level of household air pollution.
- Safety: hazards, such as fire and electrocution risks.
- Affordability: the price of the energy solution (including one-time equipment and connection costs, periodic maintenance costs, and running costs), and the income level of the user.
- Convenience: time required from the user to maintain the supply (including collecting fuel, maintaining equipment, etc.). The most modern the form of the energy supplied (compared to traditional forms), the less the time spent in maintaining its supply.

It appears clearly that improvement in energy access is not a single-step transition from ‘no access’ to ‘full access’, but a transitional progress based on the improvement of the energy attributes. Energy access entails the improvement of the attributes, by investing in physical assets but also in the development of institutions, as well as legal, policy, and regulatory frameworks. In turn, the improvement of the attributes may lift the quality of the energy access, enabling:

- The increase in energy use in terms of quantity and duration — for instance the use of more light bulbs, or for more hours a day;

- The improvement in the use of energy by allowing new energy services (e.g. space heating);
- The improvement in the quality of energy services, for example by upgrading the need from powering an electric fan to air conditioning.

The improvement of access to energy needs a multi-level set of interventions which ultimately aim at moving the consumers towards higher levels of attributes: these interventions may include new electricity connections for households, or the delivery of modern cooking or heating systems. At a higher level, it may encompass measures like policies for fostering the addition of power generation capacity, the expansion of transmission networks, or the development of minigrid systems, as well as encouraging the installation of solar home systems, biogas projects, fuel-wood plantations.

2.3 OVERVIEW OF STATUS OF ENERGY ACCESS

As emphasized by REN21 (Renewable Energy Policy Network for 21st Century, which is a multi-stakeholder network) in its Global Status Report 2016, energy access is unequal across continents and countries.

In Africa, it is estimated that nearly 60% of people have no access to reliable electricity. To understand the magnitude of the energy gap between Africa and the rest of the world, it is enough to say that Africa uses about 3% of the world's electricity (mostly within South Africa) and contributes to only about 1% of the world's carbon dioxide emissions. The entire continent of Africa has about 150 GW of installed power generating capacity. As a comparison, with 45 GW of installed capacity, the entire electricity supply of sub-Saharan Africa (excluding South Africa) is less than that of Turkey. In 2014, the electrification rate for sub-Saharan Africa was estimated at 35%, compared to 45% for the entire African Continent. (IEA, 2017)

In Asia, China and many industrialized countries, such as Malaysia and Singapore, the process of electrification is far more advanced. However, in other Asian countries, the portion of population left without access to modern energy is significant. In India, for example, 237 million persons have no access to reliable energy, which is nearly 20% of the country's population. In Bangladesh, the rate reaches almost 40%, in Pakistan 27% and in Indonesia nearly 20%. Summed up it amounts to more than 400 million people. In addition, more than 840 million people in India rely on solid fuels like firewood, dung cakes, charcoal or crop residue to meet their energy needs essentially for cooking. These are an estimated 450 million in China, 140 million in Bangladesh, 105 million in Pakistan and 98 million in Indonesia.

In the Middle East and North Africa, the global electrification rate approaches 92% but it hides extreme discrepancies: in Yemen, for example, 54% of the population (or 13 million people) do not have access to electricity, and 8 million people use solid fuels for cooking.

The situation is comparable in Latin America and the Caribbean, where in overall 95% of the population have access to grid electricity. However, 22 million people remain without access, distributed between Argentina, Bolivia, Colombia, Guatemala, Haiti, Nicaragua and Peru. About 35 million people in the region (14% of inhabitants) use solid fuels for cooking. As an extreme case, Haiti’s population (nearly 92%) relies nearly entirely on traditional cooking fuels and devices. In Honduras, Guatemala and Nicaragua access rates are below 50% (REN21, 2016).

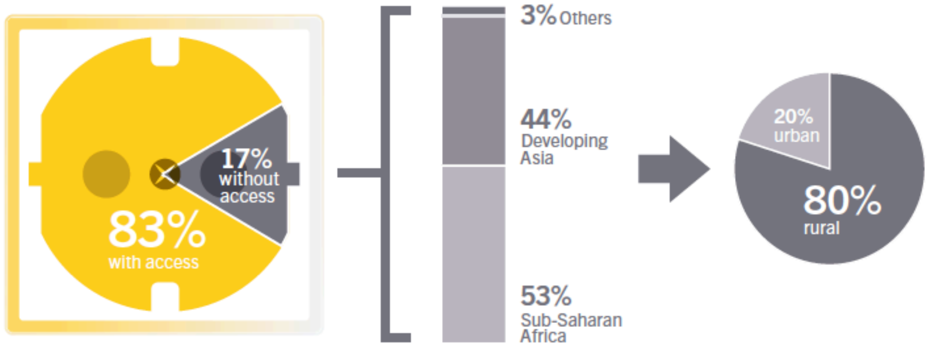


Fig. 5: World electricity lack and access. Source: REN21 (2016)

According to the Global Tracking Framework Report (SE4All, 2015), between 1990 and 2010, the share of the global population living with electricity increased from 76 percent to 83 percent, due mainly to the development of networks in the rural areas. Access to electricity outpaced population growth by about 128 millions people over the period, in the entire world, except in Sub-Saharan Africa. Contrary to the electrification of rural areas, the electrification rate in urban areas has been slower than population growth, because of rapid urbanization rates. The strongest expansion occurred in China, India, Indonesia, Pakistan, and Bangladesh. In particular, India electrified 474 million people over two decades, equivalent to an annual growth of 1.9 percent.

2.4 ACCESS TO ENERGY AS A CONDITION TO SOCIO-ECONOMIC DEVELOPMENT

The UN Secretary General’s Advisory Group on Energy and Climate Change has stressed the importance of energy for development: “a well-performing energy system that improves efficient access to modern forms of energy would strengthen the opportunities for the poorest few billion people on the planet to escape the worst effects of poverty” (AGECC, 2010).

Greater use of energy services across households, commercial and productive facilities, as well as for community facilities is essential for socio-economic development. Benefits of greater access are multiple: improved productivity, higher economic output, reduced drudgery, increased comfort, provision of basic amenities, enhanced human capital, access to education (ESMAP, 2015).

For the development advisory community, there is no doubt that energy access directly contributes to social and economic development, through the benefit of new energy services provided by the use of electric appliances. The use of basic appliances such as electric lights, phone chargers, televisions, and space coolers (such as fans) contribute to the progress in standards of living. The case of lighting helps to understand the chain of effects. There is growing evidence that electric lighting increases studying time in the evening, leading to the improvement of the access and standard of education. Electric lights would artificially extend the duration of the active day, people would then tend to stay up later at night and engage in various activities such as reading or school work in the case of children who would be able -save for other external factors (household labors especially for girls, etc) - extend studying time in the evening, which would on the medium- and long-term impact the level and quality of education as well as the availability of skilled resources in the country. Furthermore, household electric appliances may reduce the effort and time spent to perform certain kind of labor: this is particularly true for women, who may use the freed-up time made available through the use of the appliances (for instance a modern cooking or heating system would eliminate the need for the task of collecting wood) to participate in income-generating activities, or for education. Last but not least, the use of appliances may have a positive impact on health: for instance, the use of a refrigerator would improve food conservation. Or the replacement of kerosene lamps by electric lightning would reduce the risk of respiratory diseases. Electrification also enables the supply of health care services. Electrification may in some cases even generate savings due to lower energy costs, meaning higher household incomes (also because of the amount of time freed up for income-generating activities) and in turn increase household expenditure (which would foster economic development).

It is therefore understandable that "Universal access to modern energy by 2030" has been proposed as one of the three key pillars of the Sustainable Energy for All (SE4All) program, an initiative launched in 2011 and co-chaired by the United Nations (UN) Secretary General and the World Bank President.

According to IEA (International Energy Agency) projections, 12 percent of the world's population will still lack access to electricity in 2030 under the "business-as-usual" scenario (New Policies Scenario in IEA's World Energy Outlook). It is estimated that universal access to household electricity by 2030 would require an investment of about $890 billion over the period (in 2010 dollars) to reach the target set by the UN initiative.

2.5 CHALLENGES FOR ENERGY ACCESS IN DEVELOPING COUNTRIES: USABILITY AND AFFORDABILITY OF THE ENERGY SUPPLY

In many developing countries, access to energy through grid electricity faces many shortcomings like:

- Irregular supply
- Frequent breakdowns
- Low or fluctuating voltage
- Unpredictable or inadequate duration of supply (it may be limited or provided at hours when it is not really needed the most)

These shortcomings impact the usability of electricity access provided and tend to explain why there are still low adoption rate in areas where power lines and transformers are nonetheless available.

Another major challenge for expanding access is the affordability because of too high connection fees and electricity tariffs. Lack of affordability may lead to illegal usage of electricity, which is a common practice in many countries. Illegal usage may occur through many ways, like illegal connections (hook-ups), meter tampering (fraud), billing irregularities (bribery), and unpaid bills. Illegal usage may in turn cause significant financial losses for the utility, which supplies the energy, and also damage the supply infrastructure, compromising the viability of the service. With the deterioration in reliability and quality of supply, legal consumers end up being punished by paying increased electricity charges to compensate the losses, while effectively subsidizing illegal users. Illegal connections are also a concern in terms of safety as the design and the use standards of the supply infrastructure are compromised.

2.6 GLOBAL OVERVIEW OF STATUS OF POWER RENEWABLES IN DEVELOPING COUNTRIES

2.6.1 EMERGENCE OF FAVOURABLE CONDITIONS

According tor (REN21, 2016), renewable energy is benefiting from developments, which create favorable conditions for the addition of further capacity:

- Decline in global fossil fuel prices, postponing investment decisions in fossil fuel-based projects due to uncertainty and lowering fossil fuel-based investment return expectations (although it needs to be said that this development is two-fold, as it renders natural gas-based energy systems more competitive, since the price of natural gas follows the price of oil)
- The lowest-ever prices for renewable power long-term contracts
- A significant increase in attention to energy storage
- An international climate agreement in Paris in 2015 (although the USA announced that they would step back)
- New commitments like the European Union’s commitment to a binding target of at least 40% domestic reduction of greenhouse gas emissions by 2030 (from a 1990 baseline)

In the power sector in particular, the growth of renewables is driven by several factors creating new opportunities for both centralized and distributed (de-centralized) renewable energy:

- Improved cost-competiveness of renewable technologies
- Advances in renewable energy technologies
- Energy efficiency improvements
- Increased use of smart grid technologies
- Significant progress in hardware and software to support the integration of renewable energy into the energy system
- Progress in energy storage development and commercialization
- Specific and sustained policy initiatives like the UN’s Sustainable Development Goal or Sustainable Energy for All (2015)

- Better financing conditions and new financing schemes (green bonds, crowd funding, etc)
- Growing and shared concerns about energy security and environment, leading to the Paris agreement on the United Nations Framework Convention on Climate Change's (UNFCCC) during 21st Conference of the Parties (COP21) where 195 countries agreed to limit global warming to well below 2 degrees Celsius
- Growing demand for energy in developing and emerging countries (REN21, 2016)

2.6.2 RENEWABLE POWER CAPACITY IN PLACE

According to (REN21, 2016) Report, as of the beginning of 2016, renewable capacity in place was able to supply nearly 25% of global electricity (worldwide), with hydropower alone providing about 16.6%. Under favorable circumstances (i.e., with good resources and a secure regulatory framework), electricity from hydro, geothermal, onshore wind, solar PV and some biomass power sources can now even compete with power from fossil fuels on economic terms.

Although renewable electricity capacity is dominated by large generators owned by utilities or large investors, distributed, small-scale generation is growing steadily in some places, e.g. in Bangladesh which is the world's largest market for solar home systems. Also other developing and emerging countries (e.g. Kenya, Uganda and Tanzania in Africa; China, India and Nepal in Asia; Brazil and Guyana in Latin America) are increasingly turning to small-scale renewable systems, including renewables-based mini-grids, to provide electricity for people living far from the grid.

Electricity remains a priority for policy makers: many countries adopted regulatory mechanisms to promote renewable power, e.g. creating conditions for competitive bidding processes (tendering), thus driving favorable price adjustments. According to REN 21, by the end of 2015, at least 64 countries had held renewable energy tenders, with record bids in terms of both low price and high volume seen across the world's developing and emerging countries. The development of new projects and R&D in renewable energy technologies is still very much dependent on fiscal policies, including grants, loans and tax incentives.

2.6.3 CHALLENGES AND OPPORTUNITIES FOR FURTHER GROWTH IN POWER RENEWABLES

However, while in developing countries energy demand is growing rapidly, it is still fossil fuels, which dominates the primary energy mix to meet the demand (IEA, 2017).

It is worth noting that the substitution of traditional biomass for heating and cooking with more-efficient energy systems, tends to reduce overall renewable energy shares.

Financing is a major challenge too for the deployment of renewables: policy and political risks combined – as it often happens - with corruption have made it difficult to access international financing. Beyond access to finance, lack of liquidity is a problem too. But, funding for emerging markets has increased with the creation of innovative financial instruments especially for the African market, as well as with the role of companies selling distributed energy products in Africa and India.

According to (REN 21, 2016) Report, by end of 2015 renewable power global capacity was estimated at 1,849 GW, representing an estimated 28.9% of the world’s power generating capacity with hydropower able to supply about 16.6%. Wind and solar PV made up together about 77% of all renewable power capacity added in 2015.

The rapid growth of renewable power generation creates both challenges and opportunities. As electricity consumption is increasing in emerging and developing countries, the growing demand is met through both renewable energy and fossil fuel. This mix requires a transformation from centralized systems to more-complex systems including a growing number of decentralized generating assets. A key challenge is adapting the power grid to integrate the rising share of renewable generation, by developing more-flexible systems to balance variable renewable resources. Some developing countries have begun to respond to the challenge of grid integration by:

- Increasing flexibility on the demand side and on the supply side (e.g. Innovations in flexible fossil power plants; energy storage, particularly pumped storage; active power controls at wind and solar power plants). Dispatchable renewable energy plants (generating plants that can be turned on or off, or can adjust their power output accordingly to an order, as opposed to base-load plants) – including reservoir hydro, biomass and geothermal power - contribute to flexibility

- The construction of new transmission networks
- The development of smarter grids
- The interconnection and co-ordination with neighbouring grids
- Advanced resource forecasting
- And the implementation of innovative market design

There are many ways to expand energy access - from electricity grid to off-grid solutions like solar lanterns, solar home systems and minigrids, and improved cookstoves and clean fuels. Equally, improvements in supply through generation, transmission and distribution strengthening, and demand management through energy efficiency measures all contribute to energy access. The IEA estimates that by 2030, 70 percent of rural areas will be connected either to mini-grid (65 percent) or stand-alone off-grid solutions (35 percent).

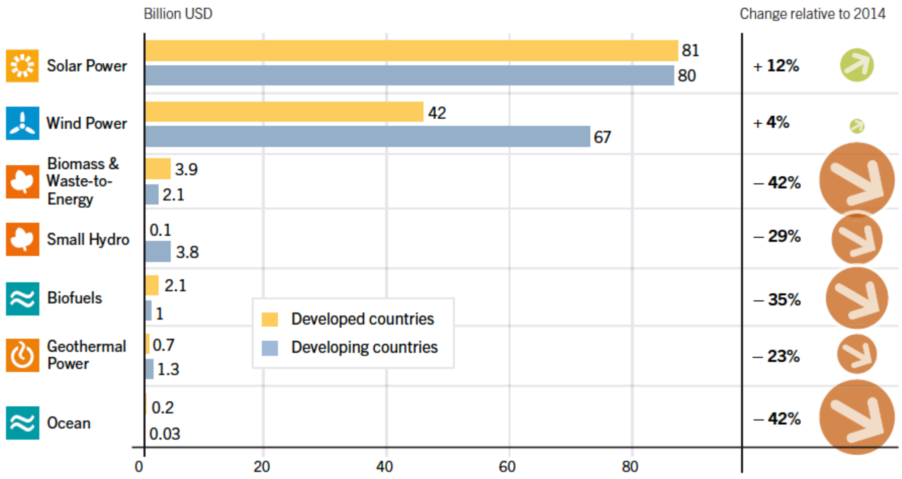


Fig. 6: Global New Investment in Renewable Energy Technology.
Source: REN21 (2016)

3 DISTRIBUTED RENEWABLE ENERGY (‘OFF THE MAIN GRID’) AS A WAY TO PROVIDE BASIC ELECTRICITY ACCESS TO LEFT-ASIDE POPULATIONS

3.1 THE ROLE OF DISTRIBUTED RENEWABLE ENERGY

Worldwide, renewable electricity production is still dominated by large generators feeding the power generated into a transmission and distribution network. Towards the end of 2015, more than half of global solar PV capacity was above 4 MW. In parallel, there are some places where distributed, small-scale generation has emerged and developed. Bangladesh is the world’s largest market for solar home systems, and other developing countries (e.g. Kenya, Uganda and Tanzania in Africa; China, India and Nepal in Asia; Brazil and Guyana in Latin America) have experienced rapid expansion of small-scale renewable technologies for remote uses.

Distributed renewable energy (DRE) systems are a solution adapted for the provision of energy services to these remote communities.

Under favourable circumstances (access to finance and adequate policy framework), DRE systems have proven to be both a reliable and affordable means for achieving access to modern energy services. Moreover, by their very nature, DRE systems are open to innovation either in technology or in the business model, and as such their spread is intertwined with the transformation of the countries.

According to (ESMAP, 2015) report, there are mainly 3 ways to improve access to energy for people in rural and remote areas:

1) By using isolated devices and systems for power generation at the household level for uses such as heating, cooking and other productive uses

2) Through community level mini- or micro-grid systems

3) Through grid-based electrification, where the grid is extended beyond urban and peri-urban areas

The advantages of more-centralized systems (#3) include generally lower costs per kW where population density is higher. It ensures also a greater load diversity and better suitability for industrial uses.

The advantages of more-distributed systems (#1 and #2) include their adaptation to the needs of small and remote communities as well as left-aside communities in urban and peri-urban areas. They are also less subject to transmission and distribution losses. The significant lower cost and the speed of deployment allow more easily for private investment. It may also foster local employment. In some cases, it may increase the security of supply, as well as improve its reliability. Last but not least, its impact on the environment is less. The decrease in size of the systems has contributed to the reduction in costs and hence to the affordability of these systems, which are all the more attractive as they may be scalable as needs and demands evolve.

DRE have experienced significant expansion especially in for cooking and heating purposes, due to factors like advances in technology, concerns about deforestation and enhanced government support. According to REN21 Global Status Report (REN21, 2016), by the end of 2015, about 70 countries worldwide either had some off-grid solar PV capacity installed or had programs in place to support offgrid solar PV applications. In addition, several thousand renewables-based mini-grids were in operation, primarily in Bangladesh, Cambodia, China, India, Morocco and Mali.

The expansion of DRE was also enabled by the emergence of innovative business models:

- Mobile payment systems and scratch cards
- The “Powerhive” business model
- Pay-As-You-Go micro-payment schemes
- And integrated service providers with products like simple solar lamps with radios and mobile phones

International programs, national policies, dedicated electrification targets and initiatives related to clean global lighting helped support DRE systems’ deployment. Furthermore, fiscal and other incentives, such as exemptions on value-added tax (VAT) and import duties greatly impact the economics of DRE systems. However In spite of promising technological developments, political instability and corruption in many developing countries make it difficult to access financing.

3.2 EXISTING TECHNOLOGIES

DRE systems include the following technological devices:

- Small-scale solar PV and stand-alone lighting systems
- Wind, biodiesel generators, and micro- and pico-hydro stations for electricity generation
- And solar and biomass heating and cooling units and cooking devices.

These technologies are adapted for uses in household, at the community scale, but also for may of them for productive and commercial purposes as well.

According to REN21 Global Status Report (REN21, 2016), it is estimated that 26 million households (equivalent to 100 million people) worldwide are served through DRE systems:

- 20 millions households alone through solar home systems
- 5 millions households through renewables-based mini-grids (usually powered by microhydro)
- 0,8 million households through small-scale wind turbines

Although the above figures appear modest in view of the challenge to provide access to energy for all, DRE systems penetrate the markets quite rapidly in many countries. As of end-2015, approximately 70 countries worldwide had some off-grid solar capacity installed or programs in place to support off-grid solar applications.

The largest market for off-grid solar products was sub-Saharan Africa (1.37 million units sold), followed by South Asia (1.28 million units sold).

An overview of deployed systems is provided below:

Pico-PV

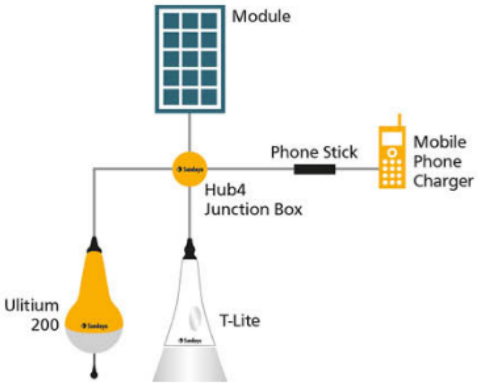


Fig. 7: Pico PV. Source: Phaesun (2017)

The smallest distributed solar PV systems are pico-PV systems (1–10 WP), which can power small lights, low-power appliances or mobile phone charging stations. They replace kerosene lamps, candles and battery-powered flashlights and are the most widely used DRE technologies by far. These systems evolve in symbiosis with the associated appliances, which use the generated power, as they typically decrease in size while the efficiency of appliances improves. According to the Off-Grid Solar Market Trends Report 2016 (Lighting Global, 2016), worldwide, some 20 million branded (as opposed to generic or un-branded) pico-solar products (mainly portable lights) had been sold by mid-2015, most of which concentrated in India and sub-Saharan Africa. In sub-Saharan Africa the market for solar portable lights has grown by 90% annually between 2011 and 2015. In India, 3.2 million solar lanterns had been sold or distributed by the end of 2015. In Pakistan, women are putting solar lanterns to productive use to start new businesses and become entrepreneurs (Lighting Global, 2016).

Solar Home Systems (SHS)

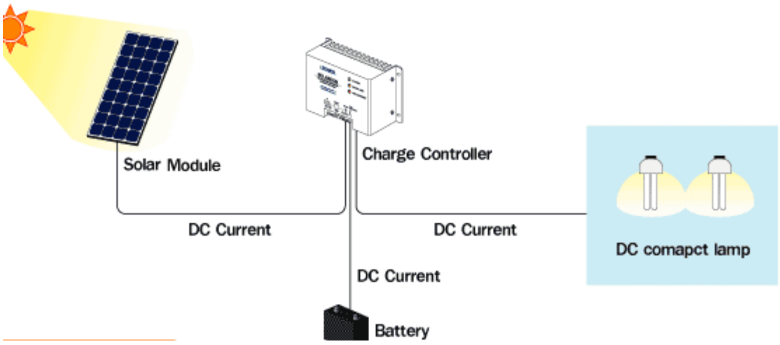


Fig. 8: Solar Home Systems connection. Source: Leonics (2017)

Solar home systems (SHS) in the range of 10–500 W generally consist of a solar module and a battery, along with a charge control device, so that direct current (DC) power is available during dark and cloudy periods. SHS provide electricity to off-grid households for lighting, radios, television, refrigeration and access to the Internet. This system may also be used for non-domestic applications such as telecommunications, water pumping, navigational aids, health clinics, educational facilities and community centers.

For higher power demands (500–1.000 W), larger solar panels, additional battery capacity and inverters to supply alternating current (AC) power may be needed. The advantages of such systems lie in their ability to power more-sophisticated electric appliances. As of early 2015, more than 6 million SHS and kits were estimated to be in operation worldwide, with Asia being the largest market by far. The SHS market in Bangladesh – the largest worldwide – has grown at an average rate of 60% annually over the past decade, with 60.000 households being connected to a SHS every month. As of early 2015, India, China and Nepal had installed over 2 million systems collectively. Around13.600 SHS (884 kW) were installed in Guyana. The SHS market also has started to kick off in Africa, particularly in East Africa. In 2014–2015, the firm M-KOPA sold about 300.000 SHS in Kenya, Uganda and Tanzania, with business expectations rising as high as hitting the target of 1 million households by end-2016 (REN21, 2016).

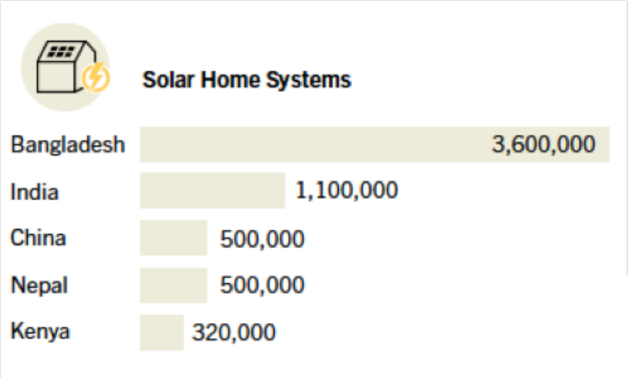


Fig. 9: Number of Solar Home Systems in Bangladesh, India, China, Nepal and Kenya. Source: REN21 (2016)

Micro- and pico-hydropower stations

Micro- and pico-hydropower stations as small as 1 kW are able to provide local communities with affordable electricity. Typically, such hydro systems can be built on existing dams and can operate reliably for at least 20 years, requiring minimal maintenance. According to Global Status Report (REN21, 2016), it is estimated that in 2015, more than 600 microhydro plants were providing electricity to of-grid rural areas in Indonesia, while in Nepal, around 1,300 micro-hydro plants and 1,600 pico-hydro systems were in operation for a combined capacity of 27.7 MW.

Biogas systems

Asia has taken the lead in the installation of biogas systems. Vegetable oil, jatropha and animal waste may be used as biogas feedstock's to substitute for diesel fuel for power generation in small-scale applications, while agricultural residues (e.g. rice husks, straw, coconut husks, shell, corn stover, etc.) may be used for commercial-scale power generation.

Small-scale wind turbines

Small-scale wind turbines (≤ 100 kW) often are used to produce electricity for farms, homes and small businesses. Off-grid applications allow rural electrification and telecommunication. They exist also in hybrid forms combined with diesel and solar PV. Total installed capacity reached 343 MW in China by the end of 2014, almost 6

MW in Argentina in 2011, 2.4 MW in India in 2012 and 0.7 MW in Morocco in 2012 (REN21, 2016).

3.3 THE NEED FOR ADEQUATE POLICY FRAMEWORKS AS WELL AS ATTRACTIVE ECONOMIC AND FINANCIAL CONDITIONS

3.3.1 INVESTMENT AND FINANCING OF DRE SYSTEMS

The two main forms of financing for investing in off-grid energy infrastructure are debt capital and equity financing. Finance may be provided by investment funds, international organizations and development banks or by private investors. Globally, a growing portion of the investments is directed to distribute solar systems. Bloomberg New Energy Finance estimated that roughly USD 276 million was invested in off-grid solar companies (solar lanterns and home systems) during 2015, bringing the total since 2010 to more than USD 511 million.

Pay As You Go (PAYG) companies alone received 87% of all such direct investments in 2014 and 2015. For example, Off Grid Electric raised USD 70 million in debt financing in 2015 to kick-start its partnership with the Tanzanian government to provide solar electricity to 1 million households over three years. Other market leaders in off-grid solar – including M-KOPA, Nova Lumos, BBOXX, Mobisol, Fenix International and Greenlight Planet – each raised investments of USD 10 million or more in 2015.

Generally, it needs initiatives from international organizations to kick-off the markets. In India, the US Agency for International Development (USAID), in conjunction with the David and Lucile Packard Foundation and the Asian Development Bank, agreed to provide financing for USD 41 million in off-grid energy infrastructure, USD 15 million in clean energy and USD 6 million for SHS. In Africa 2015, the African Development Bank launched its “New Deal for Energy in Africa”, targeting 75 million off-grid connections by 2025.

As part of the Power Africa initiative, the US Overseas Private Investment Corporation (OPIC) also agreed to provide Kenya and Nigeria with more than USD 20 million in loans to promote solar energy in 90,000 households.

The International Finance Corporation (IFC) launched a USD 5 million program to develop a market for mini-grids in Tanzania to increase access to energy, while in

Mozambique, Energias de Portugal (EDP) secured USD 1.95 million to finance a 160 kW hybrid solar/biomass mini-grid to power 900 households, 33 productive users and 3 community buildings.

Private businesses are venturing themselves more daringly into the market too.

Moving away from solar to micro-grids, the company Powerhive (United States) secured a loan of USD 6.8 million to build 100 solar-powered micro-grids (which will power about 20,000 households and businesses), and Enel Green Power (Italy) announced that it will invest USD 12 million for the construction and operation of a 1 MW portfolio of mini-grids in 100 villages.

As Juan Garcia Montes, at the time Engie's executive in charge of their African decentralized business (Engie is a multinational utility), put it (Wheeldon, 2017): "*Engie has been present in Africa for over 50 years, where it operates in the fields of electricity, natural gas and services. We are now also working on decentralized electricity production for isolated companies and rural villages and are convinced this could be a sizable part of the market because the solutions are better, subsidies are not required and technology is not an issue. It's a very, very exciting space, and is shifting from being something purely about good, charitable efforts, to being about how to build a sustainable business*."

As a first move, Engie launched its own minigrid unit, Power Corner, with 10 minigrids expected in Tanzania by the end of 2018. It has also made equity investments in several Pay-As-You-go solar companies, including Fenix International, BBOXX and Persistent Energy Ghana. Engie is hardly the only multinational utility recognizing the business potential laying in DRE systems. Firms like Enel, Eon or Iberdrola have followed the move; definitively transforming DRE markets from charity- or 'Corporate Social Responsibility'-based to business-driven.

Crowdfunding is an alternative to debt capital and equity financing. It is increasing in popularity, with many institutions managing crowdfunding campaigns to release new products or expand into new areas.

Some countries with low rates of energy access, such as Tanzania and Uganda, have implemented a number of micro-grids with funds from crowdfunding companies such as SunFunder. A crowdsourcing model launched in 2015, "Gridmates", is a webbased platform that aims to expand access to DRE systems globally by crowdfunding. In Nepal, Gham Power teamed up with other local solar companies and Global Nepali Professional Network to launch a new crowdsourced campaign called Rebuild with Sun that raised USD 150,000 for solar power systems and micro-grids.

At the COP 21 in Paris (December 2015), an array of new financing and investment initiatives was launched. For example, the African Renewable Energy Initiative (AREI), which aims to achieve universal energy access on the continent, plans to install 10 GW of additional renewable energy capacity by 2020, and 300 GW by 2030 (REN21, 2016).

3.3.2 POLICY AND PROGRAMME DEVELOPMENTS

Government policies in emerging and developing countries, ranging from regulations and financing to business support and training, are one of the most important factors for the deployment of DRE technologies, and thus expanding energy access.

Policies that support DRE deployment include auctions (in order to create competition and put a downward pressure on prices), dedicated electrification targets, initiatives related to clean renewable cooking, as well as fiscal and other incentives that focus on specific renewable energy technologies (e.g., exemptions on VAT and import duties). Many national governments across Africa, Asia and Latin America announced the expansion of existing targets and policies for DRE systems or the creation of new ones.

Beyond policy developments of individual countries, DRE programs focusing on the provision of electricity are benefiting from partnerships that involve either supranational actors (such as the United Nations) or multiple donor countries, or other actors supporting a single program. Perhaps the most significant change affecting the global policy environment relates to the United Nations' announcement of new "Sustainable Development Goals". Goal 7, adopted as one of the 17 key goals, states that universal access to affordable, reliable and modern energy services needs to be ensured by 2030. This is in line with the UN's other major energy platform, Sustainable Energy for All (SE4All), which also targets universal energy access by 2030.

The programs are designed to create favorable conditions at all levels, by actioning the full array of available levers: skill development, business support, policy advisory services, access to finance, investment in production capacities, etc. 4 types of programs are presented below as an example:

- Energizing Development (EnDev) is a partnership launched in 2005, financed by six donor countries, which helps people through training to obtain sustainable access to modern energy services in Africa, Asia and Latin America.
- The Private Infrastructure Development Group (PIDG) mobilizes private sector investment to assist developing countries in combating poverty, including through the provision of infrastructure like DRE.
- Power Africa is a partnership between the US government, African governments, multilateral and bilateral partners, and the private sector, committed to increase generating capacity and electricity access across sub-Saharan Africa.
- Energy Africa, which is a multilateral program, launched by the UK aiming at accelerating the expansion of household solar energy throughout Energy Africa campaign, by tackling financial, policy and regulatory obstacles. (REN21, 2016).

3.3.3 INNOVATIVE BUSINESS MODELS

In addition to enhanced investment and financing schemes, and adequate policy and regulatory frameworks, innovative business models have turned out to be a key for success, all the more so that international firms have recognized the potential of DRE markets and may spur the development creating a multiplier effect, by opening up new business opportunities.

To start with, possibilities of synergies were sought: therefore, energy companies began to collaborate with the telecommunications industry to design and implement solutions (such as Mobisol, a company that combines solar energy with an affordable payment plan via mobile phone). As a consequence, the use of mobile payment systems and scratch cards has grown strongly. It allows the provision of modern energy services but also creates business opportunities for people in rural areas.

Cooperation between energy and telecommunication companies, are typical for the penetration strategy of firms in potential DRE markets. In its Global Status Report, (REN21, 2016), stresses the variety of successful examples, which highlights the fact that this new market is very prone to business innovation. It is the case for SunEdison and Omnigrid Micropower Company which are electrifying rural villages in India by bringing together commercial solar customers with telecom companies that need to power their cellular towers. In this scheme, a solar-powered mini-grid is first built to power the phone tower, on which additional mini-grid capacity is developed that can be sold to local villagers.

Another example is the “Powerhive” business model (US firm) in East Africa, which combines solar PV arrays, battery storage and smart metering systems with mobile telecommunications and payment applications. Also in East Africa, the firm M-KOPA uses charging outlets for mobile phones. More than 280,000 homes in Kenya, Tanzania and Uganda have already used M-KOPA’s solar systems with mobile payment and charging configurations during the year.

May be the most representative business model is the PAYG (Pay-As-You-Go) for solar which has experienced a continuous growth. Under PAYG schemes, customers pay a small fee in advance for a solar charger kit, a portable system and a control unit that can be used for powering LED lights and charging devices such as mobile phones. The customers then pay for the energy they need, either in advance or on a regular basis depending on consumption. It is estimated that by the end of 2015, the PAYG model had been commercialized by some 32 companies operating in nearly 30 countries. It is most popular in East African countries like Kenya, Uganda and Tanzania, and also in India. But it is quickly developing in other regions as well. There are many examples of successful PAYG operations including Simpa Networks (India), SolarNow (Uganda), MKOPA (Kenya), Off Grid Electric (Rwanda and Tanzania) and Azuri (spread across sub-Saharan Africa). There are new actors entering the marker proposing PAYG schemes, but also established firms which are induced to adopt the scheme, like Greenlight Planet (in East and West Africa, and South Asia), although a market leader that has commercialized about 3 million solar lighting systems, which decided to launch its PAYG model in early 2015 to support the development of its business. It is also true for Off Grid Electric, which is installing off-grid solar devices in Tanzania for more than 10,000 households and businesses per month using this model.

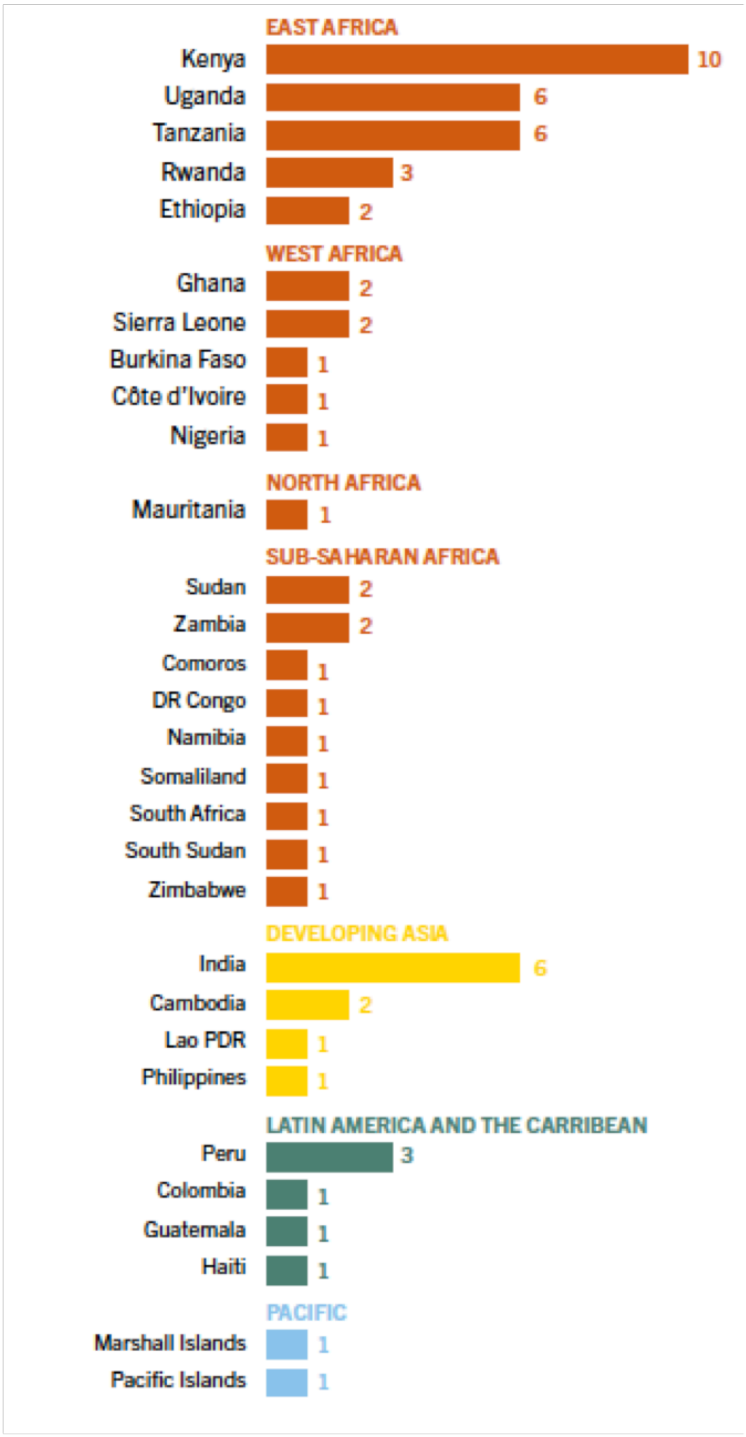


Fig. 10: Number of Pay As You Go enterprises. Source: REN21 (2016)

The PAYG models are rendered feasible thanks to mobile money payment systems, as businesses have the ability to monitor and control electricity provision remotely. It allows collecting payments very efficiently, while reducing costs.

However, there are limitations because mobile money penetration is different across all countries, so different approaches need to be used depending on the market. More critical is the fact that in the most remote and low-income communities, mobile networks don’t invest in telecoms infrastructure so relying on mobile money may be useless.

There is even the risk to trap the poorest in the vicious circle of unpayable debt as the PAYG business model is based on credit. Companies offering the scheme have a view at selling other products like TVs, etc. According to SunFunder, a solar PV financier, while users have an enforceable contract, the exposure to recourse against customers is actually limited: they would simply don’t get the service anymore. But cutting off the service is not in companies’ interest, so firms look at adapting the business model for instance by introducing payment schedules in line with expected income flows (around harvest season) (REN21, 2016).

3.4 ACCESS TO LIGHTING: A BASIC NEED

3.4.1 HOUSEHOLD ACCESS TO LIGHTING

Lighting is an energy service critical for human development. It is so much valued that households seek to ensure the service with a range of alternatives for in case electricity is not available. This is valid for both off-grid households without permanent access and grid- connected households during blackouts. These households tend to use fuel-based lighting or disposable flashlights instead. Provided with basic – but reliable - access to energy, these households would tend to fully replace these traditional systems with modern systems.

Lighting is probably one of the primary household energy demands: In early stages of history, it was provided in the form of firelight from hearths and stoves to light up the darkness. Lighting then evolved into more efficient solutions like fuel-based candles and kerosene lamps, until the breakthrough of electricity, which still fails to reach approx. 20% of the world population.

Similar to the technological leap between fuel-based and electric light with arcs and incandescent sources, light-emitting diode (LED) or “solid-state” lighting has brought about a major increase in efficiency for converting electricity into light. The efficacy (measured in lumens per watt) of LEDs recently surpassed that of fluorescent lighting and is promised to further progress.

According to ESMAP (ESMAP, 2015), off-grid lighting is enabled by the distribution of off-grid energy systems. These systems often rely on solar power. Indeed, over the past decades solar power improved its attributes, which rendered it attractive for this kind of energy service. In particular:

- It became more affordable
- It offers a wide capacity range thanks to the scalability of solar cells (from sub-watt cells integrated into some of the smallest-scale lighting devices to gigawatt-level grid-connected power plants)

The scalability of solar technologies, by lowering the cost of the individual and household-level systems, has in turn an impact in terms of affordability. This facilitates the diffusion of modern lighting solutions to a larger fraction of the off-grid population, although there are still economic barriers to access modern lighting because of liquidity constraints and limited access to financial means.

Solar systems developed in an user-based way, in order to adapt to various types of individual or household-level uses: these systems differentiate themselves mainly in terms of portability and functionality. The differences are based on the portability of the lamp (portable or fixed), and the arrangement of the solar module (integrated into the battery pack or separated with a cord).

Fixed separated systems are suitable for being used as a classic “Solar Home System”, while fixed integrated systems may preferably be used for applications such as outdoor lighting. Portable integrated products have the lowest cost and lowest performance, followed by separated lamps, and finally, fixed products.

3.4.2 BENEFITS OF LIGHTING ACCESS FOR SOCIO-ECONOMIC DEVELOPMENT

Electric lighting has positive impacts on socioeconomic conditions, by improving:

- Health and safety, by avoiding exposure to particulate pollution and other indoor air pollutants that cause chronic disease, and by reducing safety risks for users
- The level of disposable income by reducing the burden of fuel expenditure. It is estimated that the expenditure for traditional lighting systems represent between 2 and 5% of the household income. Furthermore, in the case of kerosene lamps, it is very much dependent on the price of oil, which fluctuates, and availability of kerosene in rural areas may be scarce, thus driving the price further up
- The quality of light: LED and other electric lighting are more suitable for applications like reading, writing, cooking, meaning tasks which require a certain level of clarity
- The local climate: fuel-based lighting emits more carbon dioxide compared to electric lighting. At a local level, some devices emit pollutants (such as the black carbone), which have significant air-polluting effects. Globally, while off-grid lighting users spend nearly $40 billion per year (almost 20% of all global lighting expenditures) on traditional and polluting means for obtaining illumination, they receive only 0.1% of the total lighting services consumed by the electrified world. The carbon dioxide emissions emitted in producing this inferior illumination are equivalent to that of about 30 million cars (Mills & Jacobson, 2011).

3.4.3 MINIMUM PERFORMANCE THRESHOLD FOR BASIC ACCESS

To be able to appraise the quality of the energy service provided (lighting), it is necessary to evaluate the performance standard for off-grid lighting applications. The relevant parameter for lighting is lumen-hours of lighting service per day, which is the combination of the number of hours of service with the brightness or light output for this duration.

Lighting Global which is a platform created by the World Bank to support the development of off-grid solar systems defined minimum thresholds for brightness and duration.

As referred to Global Status Report (REN21, 2016), in 2011-2012 Lighting Global performed a study among focus groups in developing countries to determine the impact of the transition from traditional lighting to electric lighting on the perception of the 'service'. It was then able to infer the threshold for brightness and for duration.

- Minimum threshold for brightness: the study showed that people making the transition are satisfied with levels of light lower than those which would be provided through access to the grid: over 90 percent of focus groups across Africa and India were satisfied with levels around 25 lumens.

It is worth noting that all lumens are not the same: the light from LEDs is more directional, compared to fuel-based lighting, which is omnidirectional. Therefore, the same luminous flux can result in substantially (~4×) brighter illumination on a surface, particularly in rooms with dark walls that absorb stray light.

- Minimum threshold for duration of lighting: the global average duration of lighting was estimated at 4 hours a day although it varies a lot across households. For instance, some households who use fuel-based lighting may use more lighting if it is available and affordable.

3.5 PARAMETERS TO APPRAISE THE LEVEL AND QUALITY OF LIGHTING

Brightness and Luminous Intensity:

Intensity was originally described using light from a burning candle, and was meant to describe how bright a light appears. Such 'standard candles' were used to define the candela, the basic unit of luminous intensity. However, a small spot of light like a candle may appear bright, but not produce enough overall light to illuminate a place sufficiently.

Luminous Flux and Luminance:

The Luminous flux, measured in lumens (lm), is typically used to describe the total amount of light that a light source produces in all directions. A lumen represents a specific perceived amount of light, and takes into account the sensitivity of the human eye (the eye is more sensitive to green light and less sensitive to deep red and deep blue/ purple).
Illuminance is the amount of light incident on a surface, measured in lumens per meter2 (lm/m2). The unit of illuminance is lux; 1 lux = 1 lm/m2.

The difference between lumens and lux is significant. A focused LED can concentrate light onto a small area, and the illuminance at this point can be very high. But the total lumen output (luminous flux) for the device can still be very low because the light is only emitted in a narrow angle (ESMAP, 2015).

Lumen Output Examples:

Standard candle = 12 lumens
Kerosene wick lantern = 8–40 lumens
Pressurized kerosene lamp = 330–1000 lumens 60 watt
GLS incandescent = 900 lumens 23 watt
Compact fluorescent = 1000 lumens

3.6 CONSUMER AFFORDABILITY OF ELECTRICITY

In just over half of the countries with deficient access to electricity, electricity is unaffordable for the poorest. For instance, Burkina Faso, the Central African Republic, Liberia, Rwanda, and Somalia have unaffordable tariffs for the bottom 20% and offer no policy support to low-volume consumers (like lifeline tariffs for example).

As shown by RISE (Regulatory Indicators for Sustainable Energy) in its 2016 report, the cost of a volume of electricity required for subsistence — estimated at about 30 kWh a month for residential users—varies among countries from US$ 1/ kWh in Somalia to US$ 0.1/ kWh in Angola, reflecting differences in costs of service and national policies. Somalia is the most expensive: 30 kWh can cost US$30 per month, far beyond the reach of the poorest 20 percent of households, almost 3 times the average household income (expressed in Gross National Income).

Burkina Faso, Liberia, Madagascar, the Solomon Islands, and South Sudan are other countries with very high tariffs. At the other end is Angola (major oil exporting country), where such subsistence consumption is a negligible share—0.06 percent of the Gross National Income per household for the bottom 20%. Similarly, Pakistan supplies almost free electricity to low-volume consumers (0.15 percent of the GNI per household for the bottom quintile). The Democratic Republic of Congo, Ethiopia, Guinea, Pakistan, Sudan, and Zimbabwe have among the lowest tariffs (RISE, 2016).

3.7 LIFELINE (OR SOCIAL) TARIFS

A majority of countries have policies to support low-volume consumers, especially through a so-called ‘lifeline’ tariff.

Cross-subsidies make subsistence electricity consumption affordable. Lifeline (or social) tariffs are targeted subsidies that are intended to improve the affordability of basic electricity needs. Any quantity of electricity consumed above this lifeline level is then charged at a commercial rate. The definition of a lifeline customer is therefore critical, and varies widely depending on countries’ incomes. For instance, Peru has a cross subsidy mechanism, the Fondo de Compensación Social Eléctrico (Electricity Social Compensation Fund), under which users with consumption below 100 kWh a month are subsidized by those who consume more than that. The subsidy is set by law, and is dependent on the typical sector and users’ consumption range.

However, the limit of cross-subsidies is that it can create distortions and deteriorate the financial performance of the utility, thus discouraging medium- and longer-term investment and development strategies. Moreover, as it tends to happen in countries with high-energy subsidies, quantity-based consumption subsidies do not easily target low-income consumers, since such households do not necessarily have access to the service or are not metered. Thus tariff reforms have lately sought to reduce the cross subsidies, or ‘rationalize’ the tariff system, with the use of subsidies limited to promoting basic consumption and making service access easier. Moreover, lifeline tariffs do not systematically mean affordable connection fees, which is an additional barrier to access as high connection fees discriminate against low-income households (ESMAP, 2015).

3.8 EFFECTIVE COST OF LIGHTING SERVICES

Poverty strikes two-fold: the lack of access to electricity induces higher costs to get the same service but using traditional means. It is the case for lighting: the effective cost of lighting is higher for people who depend on solid fuel, than it would be if they benefited from electric lighting.

In Africa half of the households use poor substitutes of electric lighting as are kerosene and candles being those very inefficient and in the long run more expensive (up to US$ 4 - 5/month according to GEA). Figure 11 compares the efficiency between different sources of lighting.

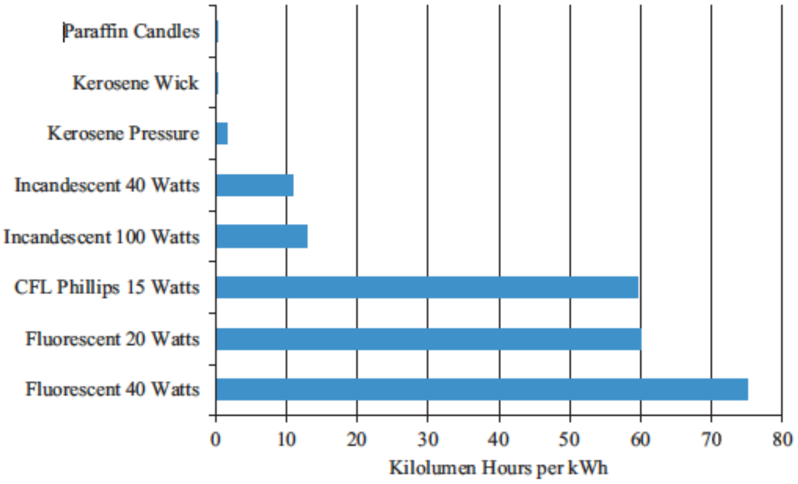


Fig. 11: Efficiency of different sources of lighting. Source: GEA (2012)

The cost comparison (Figure 12) between traditional systems based on solid fuels, a solar home system and a micro grid utility, producing the same amount of power in kWh, helps to visualize the economic disadvantage suffered from those who don't have modern access to electricity. The use of substitutes like kerosene represents a higher cost by US$3-4/kWh, while micro utility cost may be just one third of that value, depending on the country.

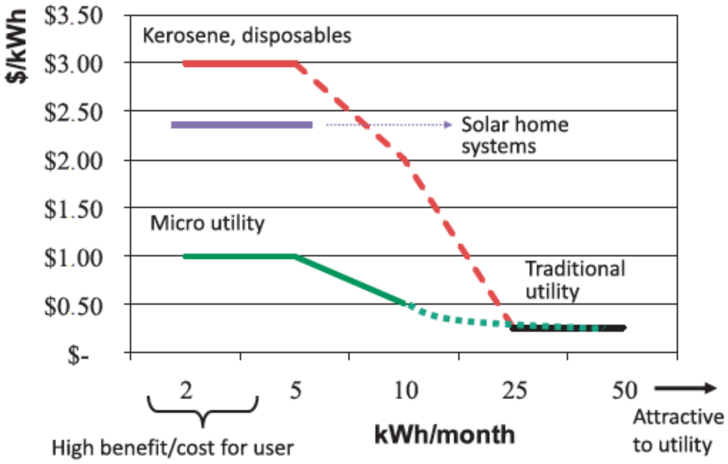


Fig. 12: Effective cost for lighting services.
Source: GEA (2012)

Lighting Global, in its Off-Grid Solar Market Trend Report (Lighting Global, 2016), used lighting assessments produced by UNEP (United Nations Environment Program) to estimate the annual burden of off-grid expenditures related to the provision of lighting services. It found that the off-grid population in Sub-Saharan countries spent about USD 14 billion in 2014, compared to USD 6,6 billion in Asia. This difference is partly explained by the subsidies for kerosene benefiting to population in India and to a less extent in other Asian countries. The cost for these expenditures may be even higher if travel time to get the fuel would be accounted for as well as the loss of opportunity created by the absorption of state funding by the subsidies.

According to Lighting's Global report (Lighting Global, 2016), annual expenditure per household varies across countries. The majority of countries would fall into the range USD 100 – USD 140 per year, with extremes estimated at USD 186 in Mauritania and USD 72 in Ethiopia. Thanks to its subsidies, India goes as far down as USD 45. Interestingly, Lighting Global found no correlation between the level of expenditure and the degree of market penetration of off-grid solar systems. Market where the penetration of solar lighting systems include countries with high levels of expenditure such as Kenya as well as countries with low levels such as Ethiopia. It seems that the degree of penetration of solar systems is not driven by the household's expenditures and income, nor by the economics (pay-back) of the system deployed.

3.9 ECONOMICS OF OFF-GRID BASIC LIGHTING SERVICE

Lighting Global (Lighting Global, 2016) performed a gross economic assessment for a household to invest in an off-grid solar lighting system. For the purpose of the exercise, it considered a 'conservative' price estimate of USD 13 for a basic portable light, which lighting service may be compared for its nature and purpose with the service provided by a kerosene lamp. The pay-back period for the initial expenditure was estimated in a range between 4 months for Kenya to 1 year for India (where the economics are distorted due to kerosene subsidies). Therefore, assuming a lifetime of two year for a quality-assured system, the users of the portable solar light may benefit of over 1 year of use at no cost, before replacement of the item. It appeared that at any case, the economics do favour the solar based system at least for basic needs over the use of kerosene-based lamps.

The main expectation is that solar PV kits, due to their relatively low price and potential applications, will kick start the markets in developing countries without public subsidies, targeting populations living in remote off-grid areas with very low income and difficult access to credit.

However the reality on the ground seems to be different with regards to affordability in case of the poorest fraction of the population in developing countries, and also in terms of willingness to pay for lighting. The question is how these populations perceive the benefits of lighting in their daily lives and whether the modern energy service will induce an improvement in their living conditions and income. Income is of course determining the affordability of the service.

Generally three types of beneficial effects can be expected from basic access to lighting, starting at the very bottom of the energy ladder, that is to say the use of a solar PV device allowing lighting one bulb. The next step of the ladder would be a device including a battery so as to be able to benefit from lighting during the night.

These effects are the productivity effect, the convenience effect and the budget effect.

The *productivity effect* relates to the time and efforts spent to produce the same or increased output in terms of housework. Housework encompasses activities like for example cooking, home cleaning, preparing beds, which are activities performed mainly by women and also in the case of children, homework.

The *convenience effect* captures the impact on people's well-being as they substitute traditional means like fuel-based lamps, for example kerosene lamps or candles, with solar PV devices, which provide better quality and more reliable lighting. Ultimately it would lead to more recreational time under light and improved health and safety conditions limiting the exposure to air polluting emittants and also household risks like fire.

The *budget effect* refers to the impact on the household income either by reducing expenditures for having access to lighting or providing new room and ways for productive activities generating additional income. It may be expected that the reduction in expenditures would free up a portion of the household income for consumption. However this would depend on the level of the household income and the degree of coverage of the most basic and vital needs, which is food and housing.

These are the effects that could theoretically be achieved and therefore influence the households' decisions to buy and use such off-grid solar devices. These households live mainly in rural off-grid areas with income as low as 1 dollar a day in average for the poorest fraction of the population. As they are focused on how to make a living on a daily basis, they can hardly project themselves in the future and assess the benefits of modern access to lighting over the long run, compared to the immediate choice of liberating a fraction of their income for buying the device. They would naturally tend to seek to cover their basic needs like food and housing in priority.

Accordingly, along to affordability, willingness to pay is the main factor for them to acquire the PV device, considering that there are different models to finance the acquisition.

An academic field study sponsored by the German Institute for the Study of Labor Economics (IZA) based in Bonn "A First Step up the Energy Ladder? Low Cost

Solar Kits and Household’s Welfare in Rural Rwanda” (IZA, 2014), assessed how the expected effects (productivity, convenience and budget) may influence the willingness to pay of the target population in Rwanda. As part of the field research, solar PV kits -certified by Lighting Africa (World Bank program) in order to provide transparency in terms of quality and consumer information, were distributed to 150 out of 300 households picked randomly in 15 remote villages for a test period of 6 months between November 2011 and July 2012. The kit consisted of a 1Watt solar panel, a rechargeable 4-LED-diodes lamp (40 lumen maximum) including an installed battery, a mobile phone charger, a radio including a charger, and a back-up battery package.

The kit is able to provide a wide range of services starting with charging the lamp’s battery, which is fully charged after one day of exposure to the sun. At full capacity the lamp can be used between 6 and 30 hours depending on the lighting intensity. Furthermore, it allows charging a mobile phone or a radio. The kit can be used to charge the back-up battery package, which in turn may be used to charge the other devices without sunlight. The market price of this kit is 29,50 USD while only the solar panel with a lamp is priced at 16,50 USD.

The purpose of the study was to target mainly subsistence farmers that live in extremely poor conditions even for Rwandan standards with a general average of cash expenditures of 1,07 USD a day per person, with the lower 25%-stratum spending 0,18 USD and the upper quantile 2,86 USD in average. According to the survey, they consume on average 3 hours of lighting per day using mainly kerosene lamps, around 11% of the households do not use any artificial lighting devices at all.

The survey showed that there was a strong preference for using the kit for lighting as technically it is the most practical, thus using up the capacity and preventing from using the kit for the other 2 services.

Based on the observation of the user patterns, three types of users could be identified: women using the lamp mainly for housework, cooking and child caring; men using the lamp for indoor recreation activities and children using the lamp mainly for studying.

Following effects were observed:

Productivity effect: children tend to shift their study time from afternoon hours to the evening hours leading to a global increase in study time. For women mainly, it provides higher flexibility for housework optimizing the organization of the day.
Budget effect: a significant reduction in expenditure for kerosene was observed as high as 70%, and the share of energy expenditures (without cooking energy) in the household budget decreased from 7% to 4%.

Convenience effect: although it cannot be ascertained because the duration of the survey was to short (6 months) it could reasonably be expected that the reduction in the use of kerosene would result in improved air quality inside the house, thus avoiding the occurrence of diseases.

The table below compares the cost of the Pico-PV kit with the traditional devices it is meant to replace.

Table 1: Cost comparison of the different sources of lighting and pay back period. Source: IZA (2014)

World Bank (2009) estimates a cost range for on-grid electrification in rural areas of	730 to 1450 USD per connection
Market price of the full Pico-PV kit Life spam	29.50 USD 2-3 years
Market price of Pico-PV lamp kit Pico-PV lamp lumen Life spam	16.50 USD 40 lm 2-3 years
Hand-crafted LED lamps (not quality assured) Hand-crafted LED lamp lumen	0.82 USD 10 lm
LED hurricane lamp (not quality assured) Battery costs to run a LED hurricane lamp Hurricane Lamp lumen	4.95 USD 0.01 USD per hour 32 lm
Battery costs to run a kerosene driven wick lamp Kerosene lamp lumen	0.03 USD per hour 12 lm
Assuming HH uses lamp 4 hours per day, pays off replacement of: LED hurricane lamp Kerosene driven lamp	After 10 months After 5 months

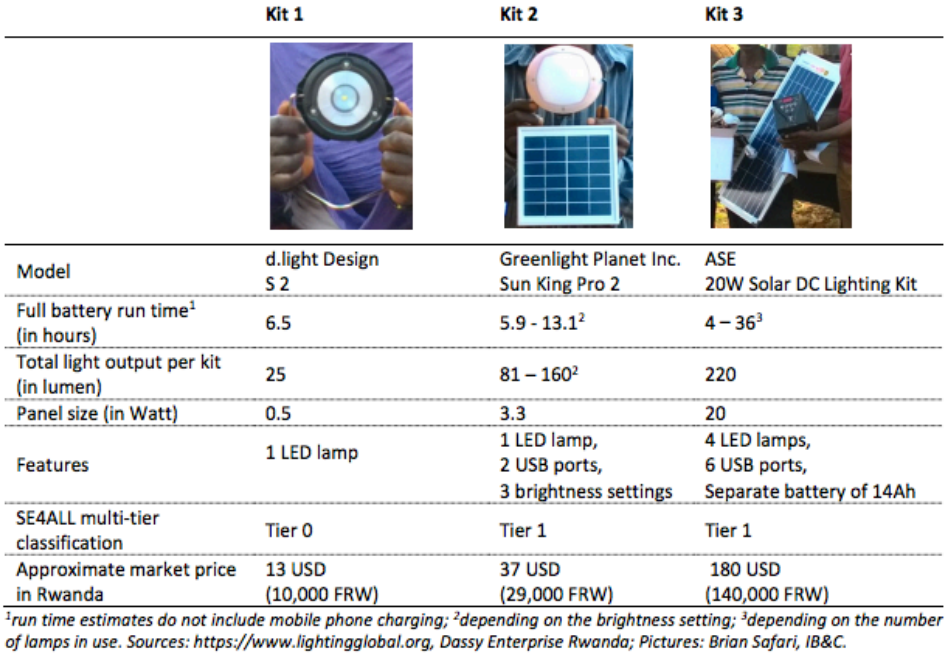
Overall the study showed that households would benefit from the substitution of kerosene lamps with solar PV kits. While it is acknowledged that the capacity of the kits is limited to the satisfaction of very basic energy needs, still, many households could not even afford the investment, which demonstrates that the intervention of international organizations or governmental institutions is necessary, for example through subsidies. Free distribution of kits would also appear as appropriate, however it entails the risk of deviating from the original purpose because households would be tempted to sell the device instead of using it. As a matter of fact many development practitioners are opposed to a free distribution policy and therefore it may be difficult to get the support of development aid programs for the implementation of such a model (IZA, 2014).

Three years later between August and November 2015, a study “Demand for Off-Grid Solar Electricity: Experimental Evidence from Rwanda” (IZA, 2016), sponsored by the same institute (IZA) and performed by the same researchers in cooperation with Rwandan institutions, proposed to assess the willingness-to-pay (WTP) of poor households living in remote off-grid areas for off-grid solar electricity devices.

According to the theoretical background – the Becker-DeGroot-Marschak (BDM) mechanism, which broadly measures WTP – 325 households were selected randomly in 16 rural communities and informed about the intention to sell them solar kits. Each household was offered randomly a specific payment period of either one-week, six weeks, or five months. However they were not told about the research purpose.

Three types of kits were offered for sale (see table 2 below)

Table 2: Specifications for solar technologies. Source: IZA (2016)



	Kit 1	Kit 2	Kit 3
Model	d.light Design S 2	Greenlight Planet Inc. Sun King Pro 2	ASE 20W Solar DC Lighting Kit
Full battery run time[1] (in hours)	6.5	5.9 - 13.1[2]	4 – 36[3]
Total light output per kit (in lumen)	25	81 – 160[2]	220
Panel size (in Watt)	0.5	3.3	20
Features	1 LED lamp	1 LED lamp, 2 USB ports, 3 brightness settings	4 LED lamps, 6 USB ports, Separate battery of 14Ah
SE4ALL multi-tier classification	Tier 0	Tier 1	Tier 1
Approximate market price in Rwanda	13 USD (10,000 FRW)	37 USD (29,000 FRW)	180 USD (140,000 FRW)

[1]run time estimates do not include mobile phone charging; [2]depending on the brightness setting; [3]depending on the number of lamps in use. Sources: https://www.lightingglobal.org, Dassy Enterprise Rwanda; Pictures: Brian Safari, IB&C.

The selected households were asked for the highest price they would be willing and able to pay. The households were willing to pay in average approximately 5 USD for Kit 1, which is 38% of the market price. For Kit 2, they were willing to pay 17USD in average, which is 45% of the market price. For Kit 3, they were willing to pay 97USD in average, which is 54% of the market price. It means that what households are willing to pay does by far not cover the price. But the significant gap between what these households were willing to pay for the kits and the market price does not mean that they lack interest in acquiring the kits, as these amounts represent a high fraction of the households' total expenditures.

Furthermore the study intended to demonstrate that liquidity constraints are not the main factor determining the decision to acquire or not the kits, as it proved to have a minor effect on the households WTP. Interestingly, when the households were offered extended payment targets, in particular when they were offered a payment period of 6 months (instead of 7 days or 6 weeks), the WTP increased for all the three kits, but at a rate lower than the interest rates offered by the local banks in case of a credit.

It may be that more favorable payment conditions, which would allow households to preserve their over-time cash flow, would encourage the adoption of the kits. But in case of the poorest households, it is assumed that they have other essential investment and expenditure priorities, impeding them to allocate the amount necessary for the adoption of basic solar systems.

The study concludes that subsidies might be necessary to support the penetration of off-grid solar technology into the most remote rural areas. Considering the cost benefit of off-grid solar technology vs. the on-grid-based electrification, it would be rational for governmental institutions to support such market intervention. Innovative market-based approaches might contribute to the dissemination of solar technologies in off-grid rural areas by offering more adapted payment and credit schemes. In particular the multiplication of "pay-as-you-go-scheme" would tend to show that the extension of the payment periods works to facilitate the investment of households in off-grid solar technology. However it does not address the problem of affordability nor solvability (IZA, 2016).

4 THE PRINCIPLE OF SOLAR PV IN AN ATTEMPT TO PROVIDE LIGHTING SOLUTION TO OFF-GRID COMUNITIES

4.1 A BRIEF HISTORY OF SUNLIGHT CONVERSION FROM ORIGINS TO TODAY's PHOTOVOLTAIC TECHNOLOGY

4.1.1 BRIEF HISTORY OF SUNLIGHT CONVERSION

The existence of fossil fuels such as coal and petroleum oil is due to the stream of solar energy which has overwhelmed the earth for over 4,5 billions years. Humans, animals, plants need sunlight to live. Without sunlight, the earth would freeze, photosynthesis would cease, plants would not create oxygen and life would hardly be possible at least certainly not in the form we experience it.

The sun is the primary source of energy for the earth. The power of the sun emits about 1400 watts per square meter on the surface of the earth: this is enough energy to power indefinitely the entire world if all the energy were converted to electricity by harnessing the solar rays with efficiency high enough (Corliss, 1964).

In history, humanity was able to transform the sunlight energy into heat or electricity, whereby the challenge was to find efficient ways to transform the energy contained in the sunlight waves into energy of motion.

With regards to heat, as early as in the 7th century B.C, it was noticed that the concentration of sunlight in magnifying glasses generates fire. Already in the 3rd century B.C, Greeks and Romans used burning mirrors to light torches for religious purposes. In the 2nd century B.C., the Greek scientist Archimedes used the reflective properties of bronze shields to concentrate the sunlight and to set the enemy's wooden ships from the Roman Empire, on fire. Anecdotally, in 1973 a similar experiment called 'heat ray' was carried out to prove the truth of the 'legend', which successfully set a wooden boat on fire at a distance of 50 meters.

Between the 1st and 6th century A.C, sunlight was used to heat the water of bathhouses and this is how the idea of 'sunrooms' was born and developed.

However, in Europe, the major technological breakthroughs happened in the decades following the period of enlightenment. 1767 is a key date, as the first Solar Collector Oven was invented. The inventor, Horace de Saussure, was a Swiss physicist, who conceived a glass box to trap solar heat. A series of development in theoretical science as well as in applied science made by mathematicians and physicists concretized by inventions from inventors which steered the direction towards technological progress, contributed to the evolution of knowledge leading to the emergence of field-proven of photovoltaic's, although with low efficiency.

The following dates in scientific history are stepstones in the exploitation of the energy from sunlight from the first heat engine to the development of the first solar cell:

- 1816: Robert Stirling built the first solar heat engine.
- 1839: Edmund Becquerel, a French physicist discovered the photovoltaic effect. He notices that voltage is generated when a given material is exposed to light.

- 1860: The French mathematician August Mouchet constructed the first solar powered engine.
- 1873: Willoughby Smith, an English engineer, discovered the photoconductivity in solid selenium.
- 1876: Professor William Grylls Adams, observed an electrical current when a plate of selenium was exposed to light. He proved that a solid material could change light into electricity without heat or moving parts.
- 1883: Charles Fritts, an American inventor, described the first solar cells made from selenium wafers.
- 1891: Baltimore (USA) inventor Clarence Kemp patented the first commercial solar water heater.
- 1904: Wilhelm Hallwachs discovered that a combination of copper and cuprous oxide is photosensitive.
- 1905: Albert Einstein published his paper on the photoelectric effect.
- 1908: William J. Bailley of the Carnegie Steel Company invented a solar collector with copper coils and an insulated box.
- 1918: Polish scientist Jan Czochralski developed a way to grow single-crystal silicon.
- 1932: Audobert and Stora discover the photovoltaic effect in cadmium sulfide (CdS).

- 1954: The technology of Photovoltaic was born. Daryl Chapin, Calvin Fuller, and Gerald Pearson developed the silicon photovoltaic cell at Bell Laboratories. It was the first solar cell able to convert solar energy into power, for the daily use. Bell Telephone Laboratories produced a silicon solar cell with 4% efficiency and later achieved 11% efficiency (EERE, 2017).

The insight provided by the above chronology is interesting as it shows that the emergence of the Solar PV technology is the result of decades of singular efforts. No guiding principle would have led directly to the achievement of solar cell technology, but it was the emerging need, which ultimately directed the efforts. Until today solar technology firms continue investigating and making improvements to increase the efficiency of the solar cells.

The solar PV technology got increasingly popular, as it is renewable and it has become more efficient and more affordable over the years: its distribution is global and it established itself as one of the most promising sources to cater for the world’s energy needs in a sustainable way (although this is also dependent on the availability of the materials used which is finite).

The most common uses of photovoltaic technology are rooftop solar power systems used to light corporations and households. Off-grid Solar panels are used to power railroads and highways. It has also established itself as a source of energy supply for batteries, for boats, vehicles, equipment, satellites and aircrafts and also in offshore navigational aids and more.

4.1.2 ACTUAL DEPLOYMENT STATUS OF SOLAR PV TECHNOLOGY

According to Global Status Report (REN21, 2016), by the end of 2015 total global (worldwide) capacity of Solar PV amounted to about 227 GW. In 2015 alone more than 50 GW of Solar PV were installed, representing approx. 185 millions solar panels. The deployment is becoming global, with new markets on all continents. In order to meet rising energy demand, developing countries have also embraced Solar PV.

Worldwide expansion of Solar PV may be explained by the following factors:

- Increased competitiveness (economic and technical)
- New government programs
- Rising demand for electricity
- Recognition of solar PV's potential as a clean energy source in order to meet environmental targets (reduction of CO2 emissions)

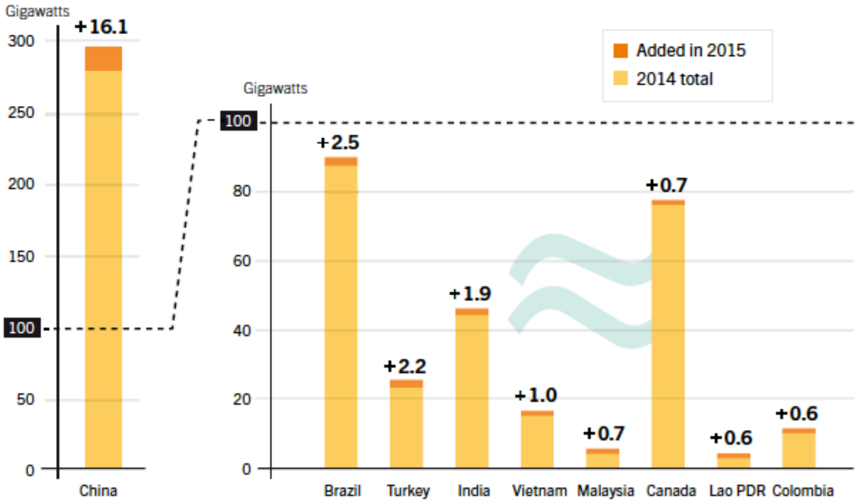


Fig. 13: Solar PV Global capacity, 2005-2015. Source: REN21 (2016)

For instance in China, the central government is increasingly becoming aware of the risks related to pollution, and set ambitious targets to increase renewable generation, also as a means to foster the domestic manufacturing industry. According to the Global Status Report (REN21, 2016), in 2015, China - with 44 GW installed (compared to 7 GW in 2012) - overtook Germany to take the global lead for cumulative solar PV capacity, with about 19% of the world total. Large-scale power plants accounted for 86% of total capacity, with the remainder in distributed rooftop systems and other small-scale installations. The downside of the rapid increase in solar PV capacity in China was grid congestion problems and interconnection delays in the country, which impeded the commissioning of new plants and resulted in curtailments. Consequently, investors tended lately to step back, also because of delays in subsidy collection and problems with solar panel quality. To address curtailment issues, the provinces with high penetration of Solar PV were requested to prioritize transmission of renewable energy, build more transmission capacity and attract more industries to increase local consumption.

As it is the case for China, grid access and financing remain a key challenges to growth in most developing and emerging economies. Deployment of Solar PV is driven by rapidly falling costs, good solar resources (depending of course on location), growing energy demand and the need to expand energy access, as well as the ambition of reducing dependency on energy imports. In Africa, projects are undertaken ranging from micro to large-scale, both on- and off-grid. But progress might be slowed by a shortage of skills necessary for installation, operation and maintenance.

In developing countries, poverty is often a major obstacle to off-grid systems' deployment. In Myanmar for instance, it is estimated that less than a quarter of the population living in rural areas have access to electricity (according to Global status report (REN21, 2016), Myanmar's overall rate of electrification was 32% in 2014, wherefrom it is inferred that the rate of electrification is even lower for rural areas only). Off-grid solar systems would appear to be an adequate solution to provide at least basic access. At present, almost all Myanmar's off-grid projects are either government-funded or donor-backed. For instance, Panasonic's fridge-powering power system is financed through charity money from Mitsui & Co; other projects may be seed-funded (a form of securities offering in which an investor invests capital at a very early stage in exchange of equity stake in the firm) by non-profit organizations or receive grants from foreign governments.

The company Myanmar Eco Solutions, a supplier of solar energy systems thought that there was an opportunity in supplying SHS (Solar Home Systems) because of their affordability compared to other solutions. However, it became apparent that it was still far too expensive for a single farmer. Therefore they had to adapt their business model, now operating with a revolving fund where farmers make small payments on a seasonal basis. According to forecasts, the capital costs of the system would be paid back within approx. 2 years.

Lack of electrification lies like a shadow over what Solar PV commercial operators might otherwise see as business opportunity, because there is no basis to forecast demand patterns, and consequently set up reliable business plans (including pricing and billing systems) to obtain finance. The chance to kick-start the market would be in providing solar systems to factories and hotels and other large-scale industrial users in urban areas, because businesses are larger users and are attracted by the prospect of reducing energy costs (Myanmar's grid-based electricity supply is not reliable and needs to be backed up with diesel generators, thus generating additional costs) (Balch, 2016).

Given the demand hurdles, off-grid solar deployment will need government support but a viable commercial model is a better guarantee over the long term, along with in-country capabilities (businesses and skilled workforce). Ideally, government and private sector actors need to cooperate.

Generally, innovative financing options and business models such as solar leases, behind-the-meter Power Purchase Agreements, green bonds and crowdfunding, are key to successful expansion. New actors are emerging or existing actors entering the market, attracted by the potential of higher profits, like solar developers and installers, investment companies and major banks. Innovative e-financing mechanisms have established themselves as enablers: In late 2015, CrossBoundary Energy (United States/Kenya) announced the first financial close of a dedicated fund for commercial and industrial solar PV in Africa through the British firm SolarAfrica.

The Global Status Report (REN21, 2016) also stresses the role of innovations: research and development aim at reducing costs by improving manufacturing processes, but also through materials substitution. It also aims at improving efficiency. Perovskites is the focus of hopes for further decrease in cost/price and increase in efficiency. Perovskite solar cells include perovskite (crystal) structured compounds that are simple to manufacture and are expected to be relatively inexpensive to produce. For the near term, for increasing cell efficiency, Passivated Emitter and Rear Cellii coating technology (PERC, which is a technique that reflects solar rays back to the rear of the solar cell rather than being absorbed into the module, thereby ensuring increased efficiency as well as improved performance in low-light environments) may be implemented in standard production processes.

Global Status Report (REN21, 2016) lists the following innovations:

- Solar windows, spray-on solar and printed solar cells. Both the firms Merck (Germany) and Emirates Insolaire (United Arab Emirates) succesfully developed new building-integrated solar PV (BIPV) products.
- “Smart” and AC modules (modules with integrated alternating current (AC) inverters that enable them to generate grid-compatible AC power) with high electronics content are offered by an increasing number of module makers in order to differentiate their products. Inverters (especially central inverters) are a key element for the overall system reliability as they address active system functions, such as power conversion and active grid support. New inverter products provide more functions, such as safety and storage management, to appeal to a broader customer base and provide needed grid services.
- Storage is the focus of research of many firms, encompassing energy storage management system vendors, startups, major inverter makers (such as Enphase (United States) and SolarEdge (Israel)), grid vendors and battery makers (e.g. Tesla, NEC and Panasonic). The firms may cooperate: the German startup Younicos develops software to control batteries, and was funded by the US thin film manufacturer First Solar in conjunction with other solar companies – including SunPower and Sharp.

In spite of technological advances, the poor quality of some cells and modules raises concern, especially about reliability and longevity. Uncertainty about energy yield has scared investors, which is slowing development in emerging and developing countries.

4.2 PHOTOVOLTAICS AND THE PHOTOSENSITIVE SEMICONDUCTOR PN-JUNCTION

4.2.1 TECHNICAL OVERVIEW OF SOLAR CELLS

Photovoltaic is the direct conversion of light into electricity at the atomic level. The photoelectric effect is the property of some materials to absorb light waves and release electrons. When these free electrons are captured, an electric current results (NASA, 2008).

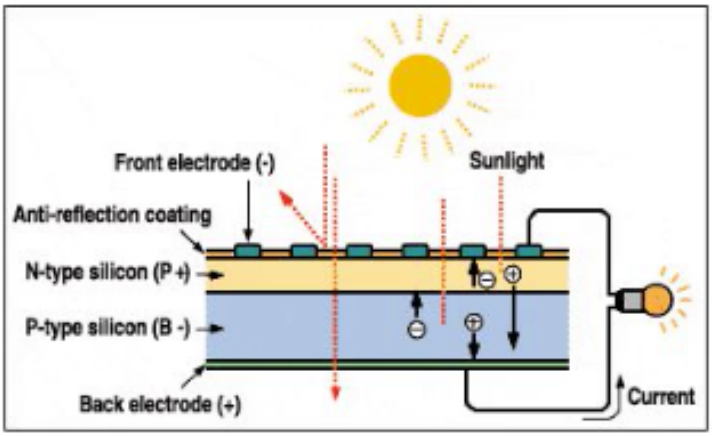


Fig. 14: Operation of a basic photovoltaic cell. Source: Honsberg & Bowden (1999)

The Photovoltaic cell also called Solar cell is - similar to diodes - made with a P-N junction from silicon semiconductor material as shown in figure 13. For solar cells, grains of silicon are treated with a substance to create an excess of electrons. This becomes the negative or N-type layer of the cell. The other layer is treated to create a deficiency of electrons, and becomes the positive or P-type layer, similar to transistors and diodes. When assembled together with conductors, this silicon arrangement becomes a light-sensitive PN-junction semiconductor.

When sunlight strikes the solar cell, electrons are knocked loose from the atoms in the semiconductor material. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons can be captured in the form of electricity. This electricity can then be used to power a load, such as a light or a tool (Anonymous, 2017).

The current produced is directly dependent on how much light strikes the module, which contains several cells. Multiple modules can be wired together to form an array. In general, the larger the area of a module or array, the more electricity will be produced.

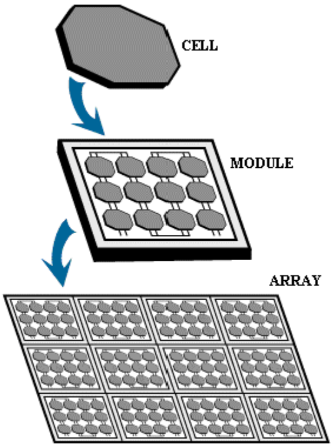


Fig. 15: Morphology of an Array. Source: Nasa (2008)

Multijunction devices can achieve higher total conversion efficiency because they can convert more of the energy spectrum of light to electricity. As shown below, a multijunction device is a stack of individual single-junction cells in descending order of band gap (or Energy Gap ‘Eg’). The top cell captures the high-energy waves and passes the rest on to be absorbed by lower-band-gap cells.

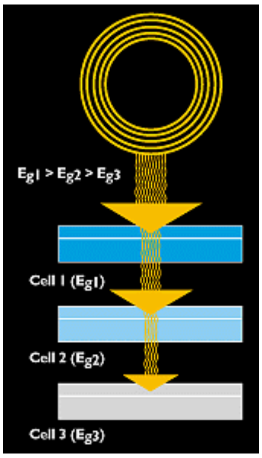


Fig. 16: Multijunction device. Source: Nasa (2008)

Gallium arsenide is one of the main components for multijunction cells for its chemical and physical properties. Such cells have reached efficiencies of around

35% under concentrated sunlight. Other materials like amorphous silicon and copper indium diselenide have also been considered. As an example, the multijunction device below uses a top cell of gallium indium phosphide, "a tunnel junction" to aid the flow of electrons between the cells, and a bottom cell of gallium arsenide. (Nasa, 2008)

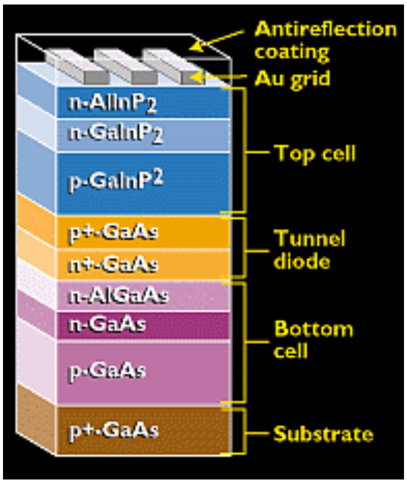


Fig. 17: Multijunction device composition. Source: Nasa (2008)

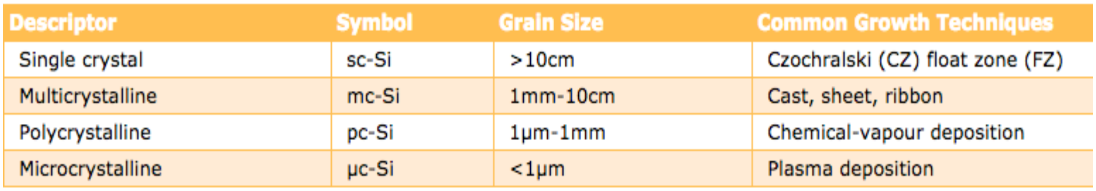
There are 2 types of Photovoltaic cells: crystalline silicon and thin film cells:

Crystalline silicon cells

Crystalline silicon is the most used material. Although it is not the ideal material for its physical and chemical properties, it has the advantage of being available worldwide in sufficient quantities. It has low weight and displays a smooth visual appearance. Efficiencies of 13-17% have been obtained with the production of silicon cells. (Fechner, H. 2015). Thickness is also an important factor. Wafers made of very thin slices of silicon are the basis for crystalline solar cells. Thinner wafers mean less silicon and therefore lower cost. The average thickness of wafers has been reduced from 0.32 mm in 2003 to 0.17 mm in 2008, while efficiency increased from 14% to 16% during the same period (EPIA, 2008).

There are different types of Crystalline Silicon cells available on the market (refer to table 3).

Table 3: Types of Crystalline Silicon c-Si. Source: Honsberg & Bowden (1999)



Descriptor	Symbol	Grain Size	Common Growth Techniques
Single crystal	sc-Si	>10cm	Czochralski (CZ) float zone (FZ)
Multicrystalline	mc-Si	1mm-10cm	Cast, sheet, ribbon
Polycrystalline	pc-Si	1µm-1mm	Chemical-vapour deposition
Microcrystalline	µc-Si	<1µm	Plasma deposition

Single crystal modules are composed of cells cut from a piece of continuous crystal. The material forms a cylinder, which is sliced into thin circular wafers. To minimize waste, the cells may be fully round or they may be trimmed into other shapes, retaining more or less of the original circle. Because each cell is cut from a single crystal, it has a uniform color, which is dark blue. Those wafers can now be cut as thin as 200 microns. The efficiency is around 18%.

Fig. 18: Monocrystalline or Single Crystal. Source: Honsberg & Bowden (1999)

Polycrystalline cells are less expensive but less efficient than single silicon. These cells are fabricated by melting and pouring the material into a mold. As the material cools, it crystallizes in an imperfect manner, forming random crystal boundaries. These cells are bigger in size per watt than the single crystal. The efficiency is around 15%.

Fig. 19: Polycrystalline cells. Source: Honsberg & Bowden (1999)

Thin film modules are made by depositing thin layers of photosensitive materials on glass, steel or plastic. Comparing with the crystalline technology the production cost is lower but the efficiency and the lifetime performance are less. Presently, thin film modules can be made of three materials: amorphous silicon (a-Si), copper indium diselenide (CIS, CIGS) and cadmium telluride (CdTe). Irrespective of the material used, the thin film is made of active layers in the thickness of a few microns (Honsberg & Bowden, 1999).

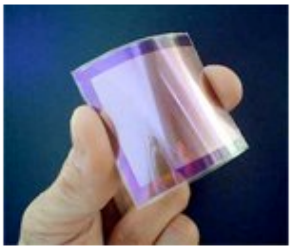


Fig. 20: Thin Film Panels. Source: Honsberg & Bowden (1999)

4.2.2 SOLAR SPECTRUM CONVERSION FOR PHOTOVOLTAIC

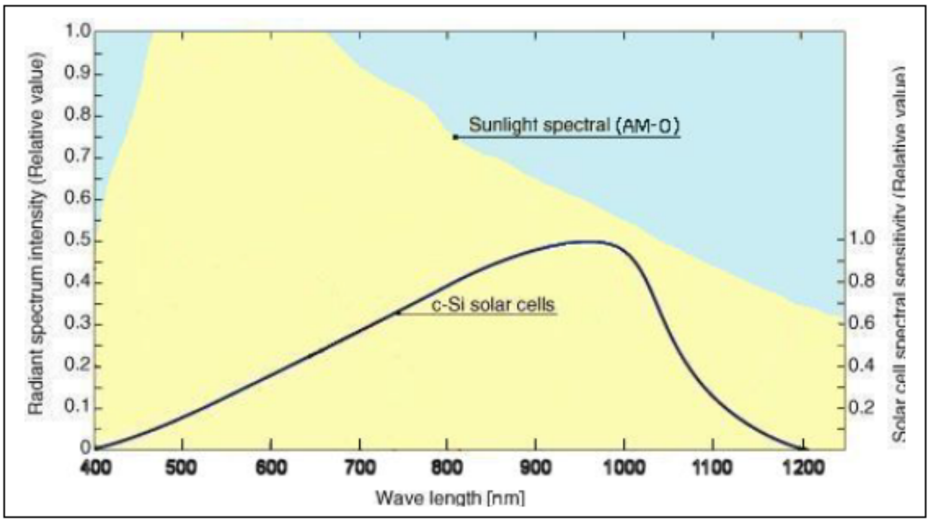


Fig. 21: Sunlight spectrum in space vs. sensitivity of crystalline solar cell. Source: Lindemann (2014)

The figure 21 above shows the relation between sun light spectrum in space and the sensitivity of the crystalline silicon solar panel to it. 'AM-0' means light outside the earth atmosphere. The peak sensitivity of the crystalline silicon according to the figure 21 ranges between 900 to 1000nm. As a comparison, the visible spectrum is between 400nm and 700nm, and the infrared spectrum begins at the red edge of the visible spectrum (700nm) up to 1mm.

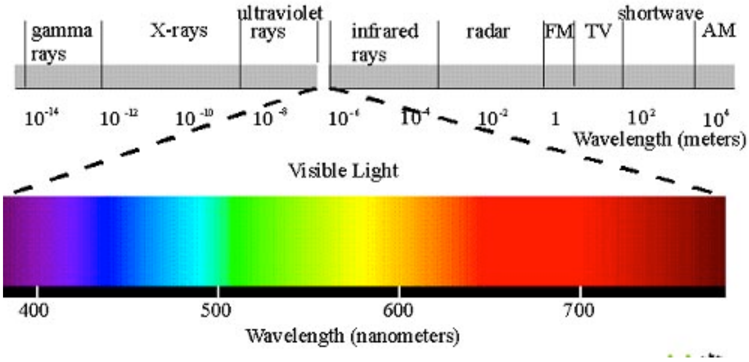


Fig. 22: Light spectrum. Source: FourPeaks (2017)

In the visible spectrum, the response of the crystalline silicon is about 20% of its capacity while in the infrared spectrum about 80% is converted into electricity. Therefore, crystalline silicon panels are used to power satellites due to its sensitive response outside the atmosphere.

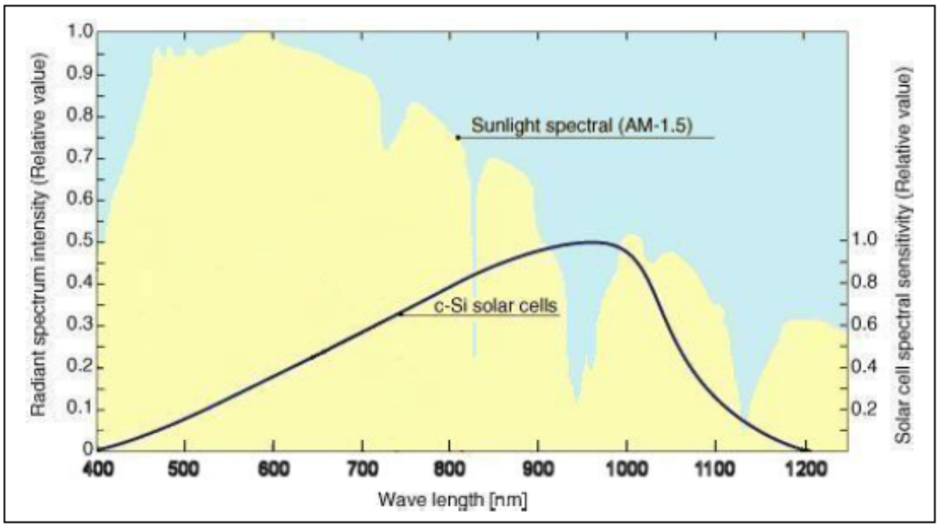


Fig. 23: Sunlight spectrum in the atmosphere vs. Sensitivity of crystalline solar cell. Source: Lindemann (2014)

Figure 23 relates the spectrum of the light that gets through the atmosphere (AM-1.5), with the solar cell spectral sensitivity. It may be noticed that some of the radiance is reflected or absorbed for the wavelength ranging from 900 to 1000nm, which corresponds to the range where the spectral sensitivity of the Crystalline Silicon panel reaches its peak.

The next graph (figure 24) shows the amount of sunlight available behind a cloud and the response of the crystalline solar cell.

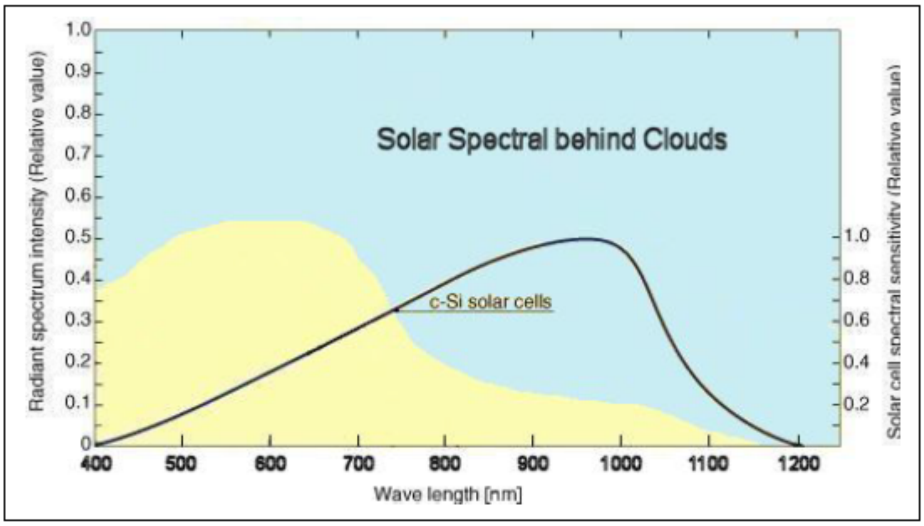


Fig. 24: Solar Spectral behind Clouds vs. Crystalline Solar Cell.
Source: Lindemann (2014)

From figure 21, 23 and 24 above, it is visible that solar cells operate mostly in infrared radiation. Only 20% of the radiation in the spectrum of visible light can be converted into electricity, which explains why solar cells are so sensitive to the presence of clouds hiding the sun, which drastically diminish the amount of power generated (Lindemann, 2014).

4.2.3 ELECTRONIC BEHAVIOR OF THE SOLAR CELL

The electrically equivalent circuit diagram of a Solar cell helps to understand the electronic behavior.

Electrically equivalent circuit model of a Solar cell

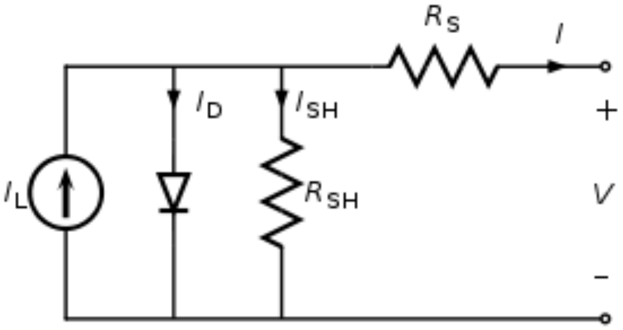


Fig. 25: Electrically equivalent circuit of a Solar cell.
Source: Anonymous (2008)

Photovoltaic modules convert light waves to direct current (DC) electricity. The electrical equivalent model of an ideal solar cell is a current power source that is a measure of the light intensity that the solar cell receives, connected in parallel with a diode (semiconductor device that permits the current to flow in one direction (forward bias) and blocks its returns). The diode corresponds to the semiconductor P-N junction. Considering that no solar cell is ideal, two resistances are added to the model.

In fact, each grain of a photovoltaic solar cell has the same properties (P-N junction) and function of a photosensitive diode. Therefore, a Solar panel is equivalent to the connection of millions of photosensitive diodes.

Based on the principle underlying the functioning of a solar cell (P-N junction), it is worth investigating whether it could be possible to use photosensitive diodes instead of solar cells to generate enough current and voltage to provide power for lighting a bulb, using e-waste, as such rendering the energy service provided more affordable.

4.3 INVESTIGATION OF THE POSSIBILITY OF USING PHOTOSENSITIVE SEMICONDUCTOR PN JUNCTION IN LEDs TO LIGHT ONE BULB

In order to develop the device, studies and investigations were made to understand the principle of light and its applications. In particular, LEDs - functioning as light detectors (as opposed to emitting light, which is their ‘expected’ function) - were identified as the key item of the device, based on the similarity between solar grain PN junction and photosensitive PN junction. Purpose of the research work is to find a way to achieve enough voltage and current for lighting a light bulb.

There are two types of photosensitive diodes: LEDs (Light Emitting Diodes) and normal photosensitive diodes. The main difference between the two types, is that LEDs are emitters and detectors of light of the same wavelength, are less expensive and commonly incorporated in many electronic appliances - meaning that LEDs significantly contribute to the accumulation of electronic waste. Photosensitive diodes or photodiodes are light detectors (not emittors), work into the wavelength of 450 to 950nm, are more expensive and not so common as electronic waste. Whereas both types of diodes present at first sight adequate technical properties, overall LEDs are more suitable for the present purpose, considering the economic constraint.

4.3.1 LEDS AS LIGHT DETECTORS

Originally LEDs were only used for emitting light, but the American scientist Forrest Marion Mims III (born in Houston Texas, 1944) has researched in the 1970s the interchangeability between solid-state light emission and detection of LEDs and published a variety of books and possible uses of LEDs as light detectors.

In the year 1998, Mims has developed an inexpensive hand-held LED-based Sun Photometer for the GLOBE program (Brooks, 2001). LEDs were meant to replace light interference filters and photo detectors in a Sun Photometer. The idea of GLOBE project was to develop a LED base Sun Photometer to monitor aerosol optical thickness, to provide information about background levels and season variability of aerosols over large geographical areas, examining urban, sub-urban, rural differences in aerosol optical thickness, tracking the movement of dust clouds and volcanic aerosols, and providing ground validation data from satellite-based aerosol retrievals.

According to Mims, LEDs are inexpensive, widely available and have extremely stable optical properties (Mims, 1992).

Other of his developments was the Solar Radiometer with LEDs as Spectrally-Selective Detectors. This solar radiometer was designed to measure the radiation emanating from the Sun and the entire sky (Mims, 2000).

Mims found out that LEDs have a peak sensitivity of a band light detection at about the same wavelength they emit. Red LEDs with a peak emission between 630 to 660nm wavelength respond best to orange light at 610nm or to their same wavelength (Mims, 2016).

In the year 2011, professor Harald Haas from the University of Edinburg at his 2011 TED Global Talk introduced the idea of another application of LEDs, the so-called LiFi, which stands for Light Fidelity: it is a visible light communication system running wireless data from every light at very high speeds.

Fig. 26: Lifi. Source: Haas (2011)

LiFi is high-speed bi-directional networked and mobile communication of data transfer using common households LED light bulbs. LiFi comprises of multiple LEDs that form a wireless network, offering a substantially similar user experience to Wi-Fi except using the light spectrum (PureLifi, 2008).

These developments have shown that LEDs could have other applications than emitting light, and that it is worth investigating whether it is possible to use LEDs as photo detectors, to generate enough voltage and power to be able to lighten a bulb (with LEDs integrated in a circuit).

For the development of the device, the scientific fundamentals of LEDs need to be understood. The central aspect guiding the research work is the property of Light Emitting Diodes LEDs as Photodiodes.

4.3.2 DESCRIPTION OF LIGHT EMITTING DIODE (LED)

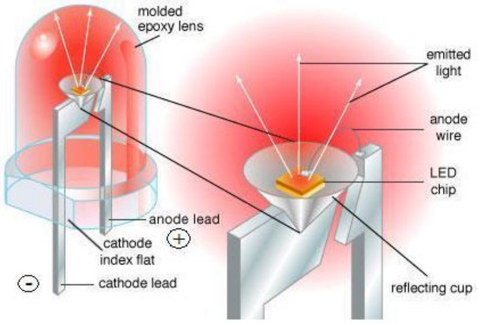


Fig. 27: LED. Source: EAI (2017)

Light Emitting Diodes, or LEDs, is a light source that uses semiconductor material and electroluminescence to create light.

Electroluminescence is the phenomenon of a material emitting light when electric current or an electric field is passed through it.

Semiconductor material is a type of material, which is an electrical conductor, but also has an electrical resistance.

A diode is a semiconductor device that permits the current to flow in one direction (forward bias) and block its returns.

LEDs exist in different types, sizes and colors, emitting light in the visible, infrared and ultraviolet spectrum. LEDs are used normally as light emitters but they have also the property of photodiodes, and as such, are light detectors as well. Photodiodes are semiconductor devices that do not emit light but convert light into an electrical current.

LEDs are implemented nowadays in applications as diverse as skin therapy (violet, red), dental curing instruments (blue), displays, flashlights, liquid crystal backlights, vehicle brake lights, traffic signals, power-on indicators and energy saving light bulbs.

4.3.3 THE DEVELOPMENT OF LEDS

In 1961 at Texas Instrument, the scientific researchers James R. Biard and Gary Pittman discovered the infrared LED. Pittman had already made experiences in the field of Solar cells and Biard had been researching intensively in the field of high electron mobility of the semiconductor material Gallium Arsenide (GaAs). Teamed up together and having the task of creating GaAs varactor diodes ("A varactor diode is a P-N junction diode that changes its capacitance and the series resistance as the bias applied to the diode is varied. The property of capacitance change is utilized to achieve a change in the frequency and/or the phase of an electrical circuit") (Skyworks, 2008) for use in reactance amplifiers for X-band (10 GHz) radar receivers, they discovered that placing a tunnel diode on Gallium Arsenide GaAs substrate, light was generated. With the help of an infrared microscope, they could see that the device lit up brightly. This discovery gave origin to the infrared LED and to the further development of different colored LEDs.

Nick Holonyak Jr., at General Electric, in the year 1962 developed the first light-emitting diode that emitted light in the visible part of the frequency range (of red color).

In 1972, M. George Craford, invented the first yellow LED.
In 1976, Thomas P. Pearsall developed a high brightness light-emitting diode for use with fiber optics in telecommunications.
In 1979, Shuji Nakamura at Nichia Corporation created the first blue LED.

In the following years LEDs were put on the market, but at high prices, so it was mainly major corporations with strong R&D capabilities, which were able to take the risk to use them. IBM happened to be the first company to incorporate LEDs in their computers.

Step by step, thanks to innovative methods for streamlining their production, LEDs became a mainstream commercial product and nowadays LEDs are integrated in almost every electronic device.

4.3.4 STRUCTURE OF LED

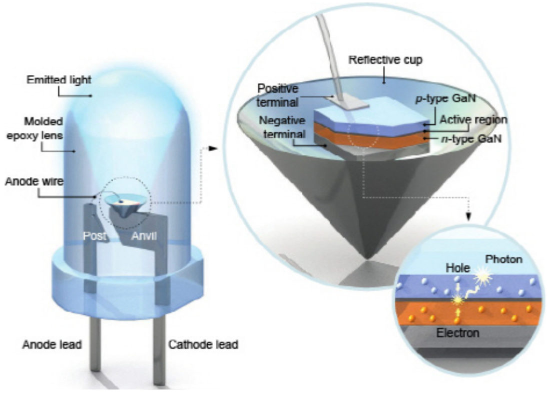


Fig. 28: LED structure. Source: IEEE (2009)

Light emitting diodes are made of a very thin layer of heavily doped semiconductor materials. Depending on the semiconductor material used and the amount of doping, when the current flow in one direction a LED will emit a colored light at a particular spectral wavelength.

LEDs are formed by a union of N and P-type semiconductors. P-type material is formed by adding a substance deficient in electrons, commonly called a dopant (silicon, germanium, gallium arsenide, or some other semiconductor). When a crystal is formed out of the material, it will then be classed as P-type semiconductor. Since the dopant tends to borrow or accept electrons from the host material, it is called an acceptor dopant. N-type semiconductor material is formed by adding a dopant with an excess of electrons to a molten batch of semiconductor material.

In order to maintain equilibrium, the dopant donates electrons to the host material and is therefore called a donor dopant. Zinc is a typical acceptor; typical donors are tin, tellurium, and silicon. Practical p-n junctions, that is unions of P and N semiconductors, are formed by heating a wafer of N-type material in a furnace in the presence of acceptors. The acceptors diffuse into the wafer, forming a P-type region as shown in figure 28. The border between the P and N regions is the so-called P-N junction (Mims, 1972).

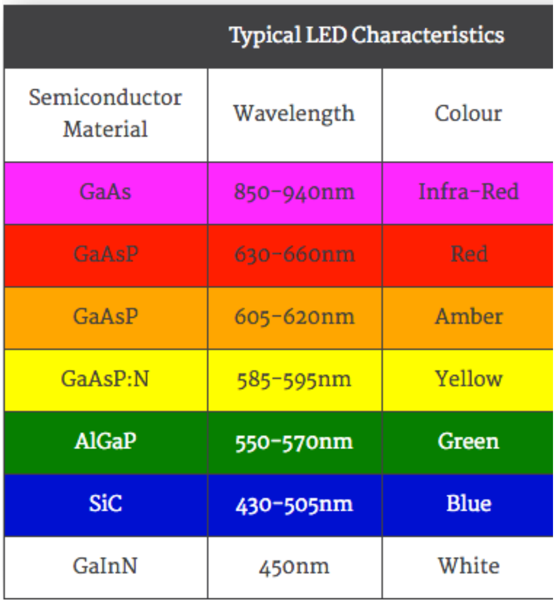
Although semiconductors LEDs are designed as light sources, LEDs can function as very stable, spectrally selective photodiodes (Mims, 1973).

4.3.5 LIGHT EMITTING DIODES COMPOSITION

Light Emitting diodes get their color depending on the type and amount of semiconductor compounds that they are made from.

Gallium (Ga) is the most used element for the development of semiconductors (table 4). Gallium Arsenide (GaAs) in a LED produces light in the infrared range and Gallium Arsenide Phosphide GaAsP produce light in the range from red to yellow, depending of the quantity of phosphorus. Adding Aluminum to GaAs produces GaAlAs, giving a super bright red color light with high efficiency. Blue and most green LEDs are made from Gallium Nitride (GaN). Green LEDS can also be made from Gallium Phosphide (GaP). (AZOOPTICS, 2016 and Mims, 1992)

Table 4: Typical LED Characteristics. Source: Tesla (2017)



Typical LED Characteristics		
Semiconductor Material	Wavelength	Colour
GaAs	850-940nm	Infra-Red
GaAsP	630-660nm	Red
GaAsP	605-620nm	Amber
GaAsP:N	585-595nm	Yellow
AlGaP	550-570nm	Green
SiC	430-505nm	Blue
GaInN	450nm	White

Therefore the color of the light emitted by the LED is determined by a very specific mix and amount of P- and N-type semiconductor materials, which in the same way predetermines the wavelength of light that the LED receives. It is important to note that the color of the plastic body of the LED does not determine the color of the light emitted.

4.4 PROBLEMATIC OF E-WASTE IN DEVELOPING COUNTRIES

E-Waste is a term for designating electrical and electronic waste, such as personal computers, office equipment, televisions, mobile phones, printers, refrigerators, air conditioning, entertainment device electronics that had become unwanted, obsolete or just had reached the end of their useful life. E-waste is the category of waste with the highest growth rate worldwide (UNODC, 2011:110, cited by ABI Research, 2009).

According to the United Nations Environment Program (UNEP), more than 50 millions tons of e-waste are generated every year, and just 10% is being recycled.

The effect of rapid innovation on the emergence of new electronic technologies, continuous product development, programmed obsolescence and the customer's obsession of the customer to be in possession of the newest technologies with no after-thoughts about wasting, recycling or reusing, are the main reasons for e-waste growth. European Union (EU), the US and the UK are the main generators of e-waste. In terms of per capita e-waste generation, the UK is in front with a rate of 15 kg per capita and per year, followed by Germany 13.3 kg, while Japan generates 6.7 kg and China only 1.7 kg (Ongondo et al., 2011).

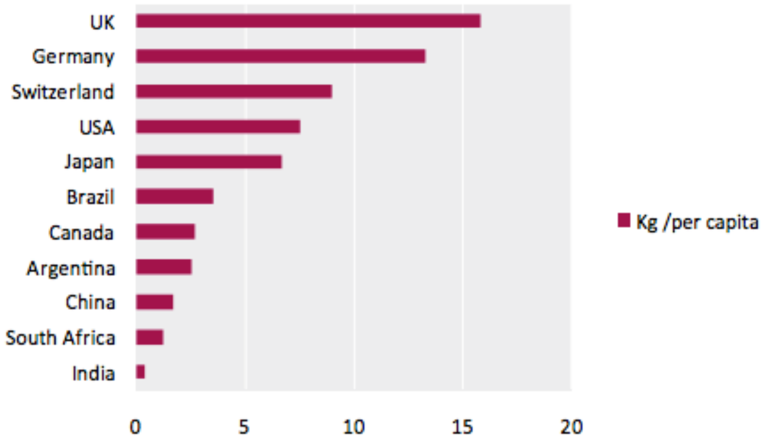


Fig. 29: E-waste generation per capita. Source: Ongondo et al., 2011

The e-waste trail often begins in Europe, the United States and Japan, where discarded electronic and electrical equipment is collected by recycling operators.

Although depending on the country's regulations and practices, normally e-waste must be discarded either by private consumers who dispose of used equipment at municipal waste collection sites, or in the case of firms or public entities by a subcontracted specialized waste management company which collects and treats the defunct equipment.

However the rules are often circumvented which explains the existence of an e-waste black market, to avoid the cost of recycling and receive payments from scrap equipment. (Secretariat of the Basel Convention, December 2011). In particular, the low cost of shipping containers from United States and Europe to China makes this black market very lucrative: after the cargo delivers the containers from China, it would use the opportunity to transport e-waste instead of returning empty. There is also an indication of transboundary movement of e-waste between Africa and Asia.

Therefore, what drives the illicit trade is a combination of two factors: the market value for commercial metals and other elements found in e-waste plus the effort to avoid paying the price for safe recycling.

The Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal (1992) regulates the trade in hazardous and other wastes. The Convention was developed in response to a series of scandals in the 1980s involving the dumping of toxic waste in developing countries.

E-waste may be classified as hazardous waste due to the presence of toxic materials which can be considered either hazardous or non-hazardous waste in accordance with the Basel Convention, and have adverse impacts on both the environment and human health. Some e-waste contain very toxic substances such as mercury, lead, cadmium, arsenid. Those toxic materials can cause cancer and many other illnesses if not recycled properly.

The informal recycling of illicit e-waste has become a serious health and environmental issue, especially in developing countries where e-waste is not treated as per proper standards and methods. The whole community may be affected by health problems, as is the case in Guiyu, China’s Guangdong province, which is the center of the informal recycling system in China: from 10 inhabitants 9 suffer skin, respiratory or digestive problems. The burning of cables to get to the copper, the lead emissions from heating up the printed circuits, the use of acids to separate the copper and gold from boards. The water, soil and air get contaminated from toxic components. All of this impacted severely the health of the inhabitants.

To face the problem, the World Customs Organization (WCO) and UNEP created the Project Sky-Hole Patching against illicit e-waste trade. In the year 2007, between March and October the Hong Kong Customs intercepted 98 illegal shipments of hazardous waste from 25 countries, predominantly the European Union, Japan and the United States.

In spite of the efforts and initiatives, it is still necessary to strengthen the awareness with regards to illicit and health- and environment-adverse practices as well as to develop the monitoring of e-waste recycling. New legislations are needed along with the promotion of preventative measures, helping to promote an ecofriendlier and cleaner environment. Regrettably, developing countries are the ones which suffer the most, even though they are not the generators of e-waste, due to the ‚not in my backyard' mentality. Governments need to realize the harmful effect e-waste has had on the environment, and the health issues it has caused in those countries. For now, exporting e-waste is hardly a sustainable practice (UNODC, 2013).

5 DESCRIPTION OF THE DEVICE AND TEST RESULTS

5.1 DESCRIPTION OF THE INTENDED DEVICE

The original idea was to use a semiconductor pn junction together with an amplifier oscillator circuit, which exposed to sunlight, generates enough electricity to light a bulb (Figure 30).

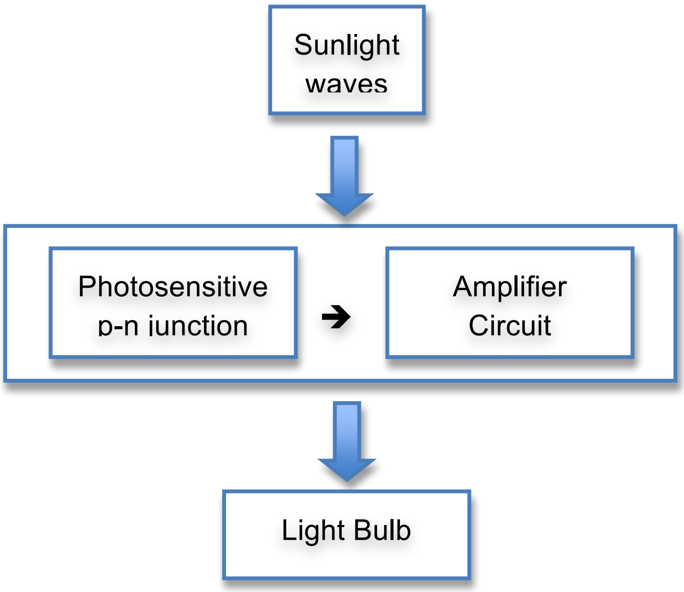


Fig. 30: Diagram of the main idea. Source: Own graph

The circuit diagram is represented in the figure 31. The main source of power is the pn junction that in conjunction with the sunlight would generate enough voltage and current to power ON the transistor. The amplifier circuit works like a blocking oscillator, increasing the energy of the power supply (pn junction) by changing the constant input voltage into consecutive quick pulses at a higher voltage.

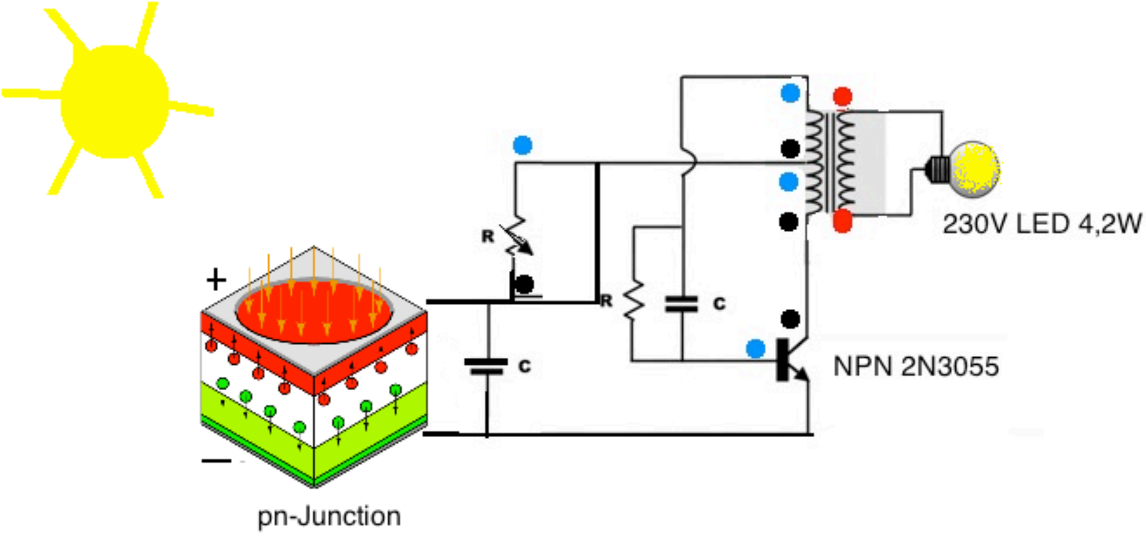


Fig. 31: Circuit Diagram. Source: Own graph

The amplifier circuit is based on NPN transistor (2N3055) and a coil.

In a transistor there are two paths for the current: one is between base and emitter and the other is between collector and emitter figure 32. In a standard NPN transistor, intended for the device, a voltage of about 0.7V between the base and the emitter is needed to get the current flowing from base to emitter. When 0.7 Volts are applied from base to emitter, the transistor is turn ON and allows a current to flow from collector to emitter.

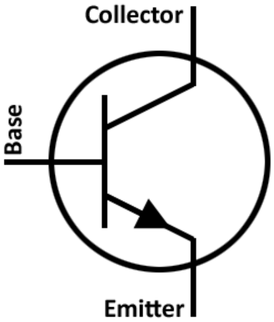


Fig. 32: NPN Transistor. Source: Triztian (2013)

When the circuit is powered on, a small amount of current goes through the variable resistor (figure 31) and the first coil (blue color), then from the base to the emitter of the transistor (NPN 2N3055). If the transistor is turned ON, the path from collector to emitter opens and electricity can flow through the second coil (black color) and then through the collector-emitter channel of the transistor.

Since the represented blue and black coils are connected opposite to each other, the current in one coil will flow opposite to the current in the other coil. This will generate a magnetic field inside the coil. The changes in the magnetic field will induce a greater amount of electricity in the other coil (red color), which is physically situated inside the blue and black coils.

The electricity induced in the first coil goes through the base of the transistor and opens the path from collector to emitter, allowing even more electricity to travel from collector to emitter of the transistor. This process gets repeating until the path between collector and emitter is fully open and the base of the transistor gets saturated. At this point, there are no more changes in the magnetic field and the voltage induced gets reduced, meaning that the current in the base gets reduced too. The path between collector and emitter begins to close and the process starts to reverse, closing down the paths between collector and emitter and base and emitter. Since the current gets reduced the magnetic field collapses as well but in opposite directions as before generating a current through the capacitor, thus charging it.

This generation of a magnetic field inside the blue and black coil induces an even bigger magnetic field in the red coil which is inside the other 2 coils, generating a high alternating current (AC) and voltage, expected to be enough to light the light bulb. And this process gets repeated over and over, until there is not enough energy coming out from the power supply (pn junction).

The elements used in this circuit can be easily found in obsolete electronic appliances (old radios, old microwaves, energy saving light bulbs circuits...). The material used for the coil can be taken from an old motor (copper wire), meaning that these elements may also be found as electronic waste.

5.2 TESTS AND COMPARISON OF OUTPUT RESULTS

The graphic below shows the LEDs used for the first test: 5mm and 10mm diameter LEDs.

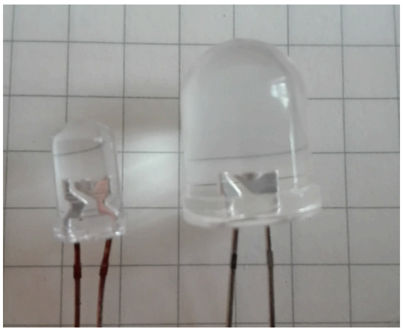


Fig. 33: 5mm and 10mm diameter LEDs. Source: Own picture

The current and voltage from five different light color 5mm LEDs were measured to determine the best results of voltage and current output (Figure 34).

The figure 34 below shows the results from the different light color 5mm LEDs (red, infrared, blue, green, yellow): It appears that the LED of yellow light color gave an output of 2,2v voltage and 13uA current, providing the weakest photosensitive response. The LEDs of other light colors generated both more current. The "red light" LED being the one displaying the highest current output, around 50 to 100uA and a voltage of 1,6 volts.

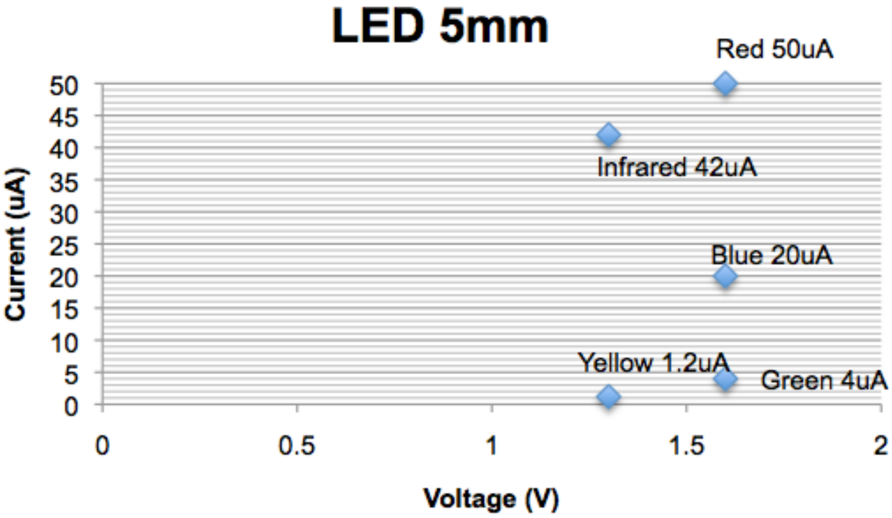


Fig. 34: Test LEDs 5mm. Source: Own data

The next test was performed with 10mm diameter LEDs, using the same colors as in the previous test with 5mm LEDs, so as to be able to compare the photodiode property of the different colored LEDs in respect of the size.

Graphic 35 below illustrates the behavior of the different LEDs tested. As it was expected, the LEDs display the same ranking by color in function of their current and voltage output, as the ranking of the 5mm LEDs (Graphic 34), although better results: The yellow color generated 13uA and the red color provided the strongest photodiode response with a maximum current output in the range of 150 to 200 uA, and a voltage of 2,2Volts.

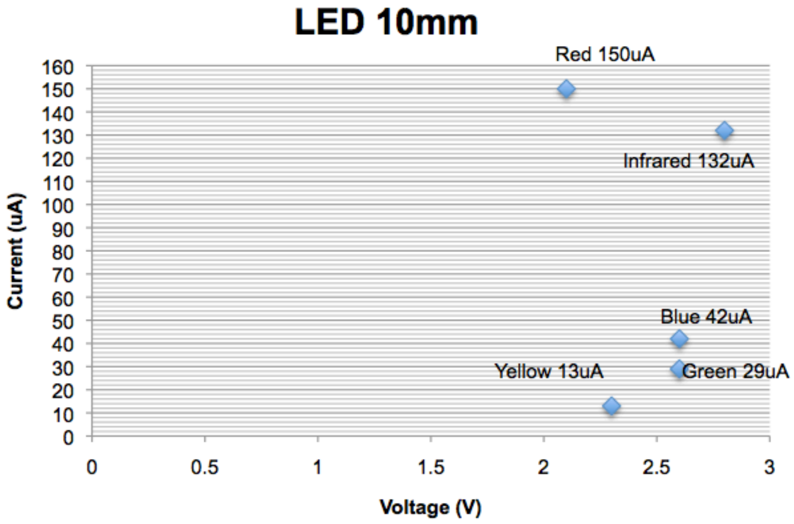


Fig. 35: Test LEDs 10mm. Source: Own data

Subsequently, following the methodological approach, further tests were performed with different types of LEDs, like the LED strip 5050 (figure 36). The strip consists of SMD LED Modules (surface-mounted device light-emitting diode module) which is a type of high power LED light module that uses surface-mounted technology (SMT) to mount LED chips on Printed Circuit Boards (PCB). The dimensions of the chips are 5.0mm x 5.0mm. Every chip consists of 3 white color LEDs covering the range of the visible spectrum in the range of 400-700 nanometers in wavelength. 5 meter of white light LEDs (LED strip 5050) was exposed to the sunlight, and voltage and current respectively measured. The results (table 5) were not satisfactory taking into account the size of the strip and the number of LEDs.

Fig. 36: White LED strip 5050. Source: Own

Table 5: Test result white strip 5050. Source: Own measurement

Max. Voltage	6 volts
Max. Current	0,22 mA

Another type of LED was the RGB LED strip (figure 37), which was tested as well. RGB LED means Red, Green and Blue color LED. In this type of strip, each color LED has its own chip, meaning that they can be individually measured.

For this test, 4 meters of RGB LED strip was exposed to the sunlight and every color LED was measured separately. The voltage and current output are shown in table 6. In front of the high voltage output, the current output is very weak. Connecting the three colors RGB in series produced an output voltage of 16Volts and a current output of 0,03mA; unfortunately this little current is too low with respect to the current output needed for the purpose of this work.

Table 6: Test result white strip 5050. Source: Own Measurements

Color LED	Voltage	Current
Red	4,3 Volts	0,04mA
Green	5,6 Volts	0,02mA
Blue	6,6 Volts	0,03mA
RGB	16 Volts	0,03 mA

Fig. 37: RGB LED strip. Source: Own

Another type of LED is the High Power LED: For this work, the High power LED, 1W, red color, was used for outdoor sunlight testing (figure 38). The results were disappointing. The voltage is high but the current response is very low (table 7).

Fig. 38: High Power Led 1W.
Source: Own

Table 7: Test result high power LED.
Source: Own measurements

Max. Voltage	3 volts
Max. Current	5 uA

Output comparison

In comparing all the output results from the different types of LEDs tested, the most successful outcome in terms of current and voltage was the Red color LED, 10mm. However, the resulting output (150 uA current) is not sufficient for lighting a light bulb.

Based on this result, a new test with 12 red 10mm LEDs, connected in parallel as shown in graphic 39. A parallel connection to increase the amount of current was performed.

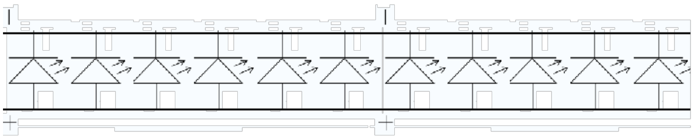


Fig. 39: Parallel connection 10mm LED. Source: Own figure

The purpose of this test was to prove an increase in current that should be directly proportional with the number of LEDs connnected in parallel.

The results of this test (figure 40) show a high increase in current output, which is as expected dependent on the amount of LEDs connected.

In this case 12 LEDs gave a maximum current output of almost 1mA and a constant voltage of 1,4volts.

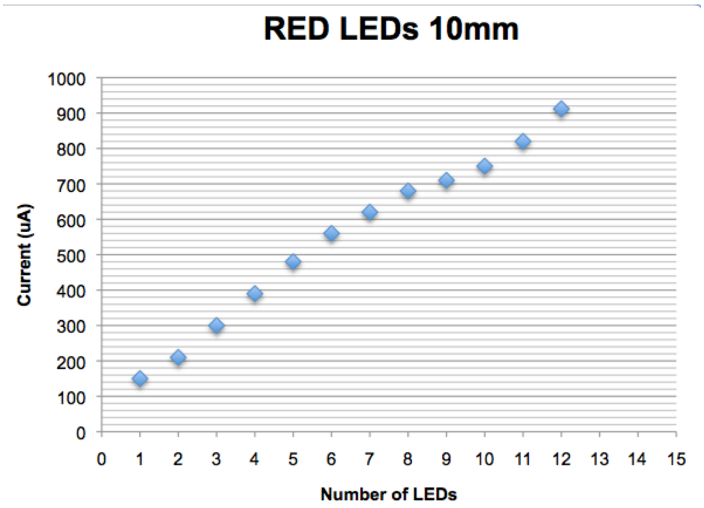


Fig. 40: 12 LEDs 10mm connected in parallel. Source: Own data

According to the graph (fig.40), the linear formula F (x) that represents the amount of current generated in microamperes and can be expressed as a function of the number of Leds (x) connected in parallel:

$$F(x) = 67{,}41(x) + 110{,}86$$

Formula 1: LEDs 10mm connected in parallel. Source: Own data

Furthermore, to discard any reflection of sunlight as it hits the surface of the LED due to the epoxy lens, a hole was bored into the center of the 10mm LED, above the wire that makes contact with the chip and the reflected cap (figure 41). The hole was drilled with a 6mm bit, minding not getting too close to the wire.

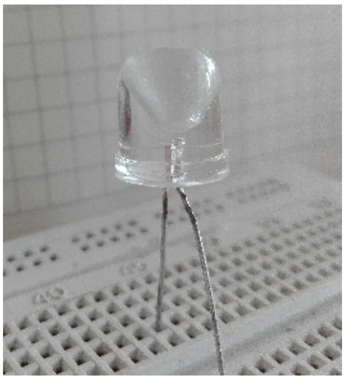


Fig. 41: 10mm bored LED. Source: Own

The results are illustrated in figure 42. Twelve red bored LEDs of 10mm connected in parallel and exposed to sunlight produced a current which decreased by more than 70% comparing with the unbored LEDs (figure 40), but the voltage increased by more than 50%: 3,6 volts compared to the 1,4 volts for the previous test.

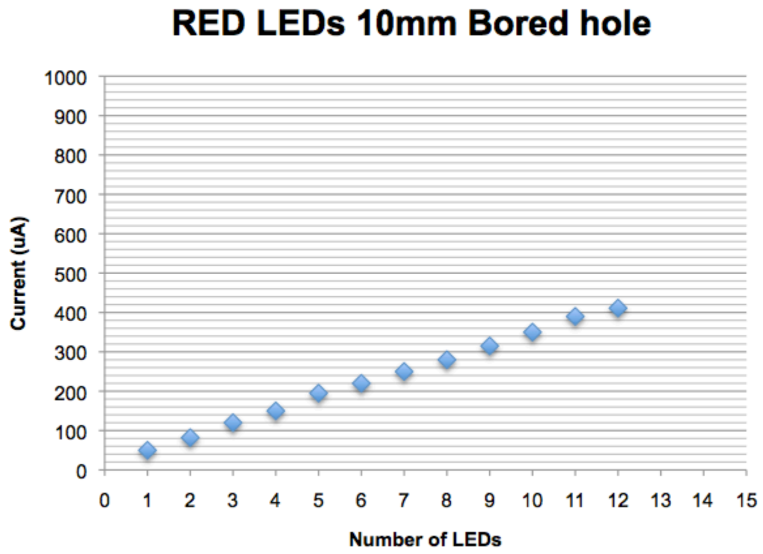


Fig. 42: 10mm red LED bored. Source: Own measurement

According to the graph (fig.42), the linear formula F (x) that represents the amount of current generated in microamperes and can be expressed as a function of the number of Leds (x) connected in parallel:

$$F(x) = 33{,}09(x) + 19{,}35$$

Formula 2: 10mm red Led bored connected in parallel. Source: Own data

As a further attempt to increase the output, a magnifier or a Fresnel lens could be fixed onto the LED, as it is expected to have a positive impact on the resulting output. According to calculations (see sub-section below), the current needed to light a LED light bulb is around 410mA (see next sub-section), with a voltage of 12 volts. This means that the LED-based device has to generate this amount of current and voltage to light the LED bulb. In this case, 12 LEDs gave a maximum current of almost 1mA and a constant voltage of 1,4 volts.

In order to reach the voltage required of 12 volts, 9 LEDs need to be connected in series and to reach the current needed of 410mA, it is necessary to connect 4900 LEDs in parallel. This means connecting altogether 44.100 LEDs.

5.3 CURRENT AND VOLTAGE CALCULATION TO DETERMINE THE POWER REQUIRED TO LIGHT BULB

The purpose of the work was to develop a device that can at least light one bulb. Therefore, it is necessary to know the amount of current, voltage and power required.

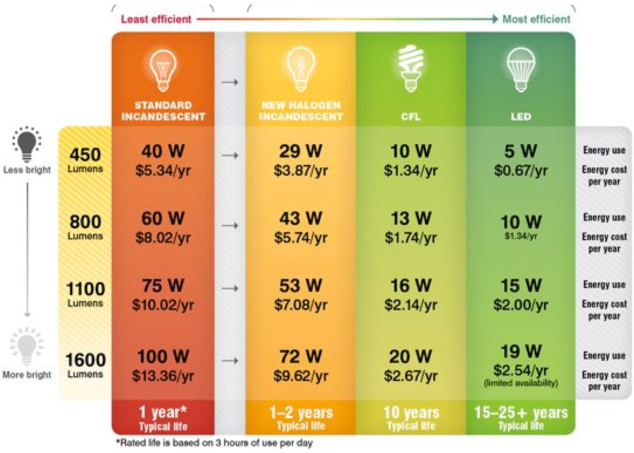
The minimum current that is needed for the circuit, to power a light bulb is calculated with the Ohms Law (formula 3). According to the Ohms law, the current flow through a conductor between two points is directly proportional to the voltage applied across the two points.

Fig. 43: Current flow through a resistor. Source: Gross & Roppel (2012)

$$V = I * R$$
$$P = V * I$$

Formula 3: Ohms Law

Figure 44 illustrates a comparison in energy efficiency between standard incandescent light bulbs, new halogen incandescent, CFL and LED light bulb. It appears clearly (figure 44) that LED light bulb has the highest efficiency, lowest cost and longest durability.



Least efficient → Most efficient

		STANDARD INCANDESCENT	NEW HALOGEN INCANDESCENT	CFL	LED	
Less bright	450 Lumens	40 W $5.34/yr	29 W $3.87/yr	10 W $1.34/yr	5 W $0.67/yr	Energy use Energy cost per year
	800 Lumens	60 W $8.02/yr	43 W $5.74/yr	13 W $1.74/yr	10 W $1.34/yr	Energy use Energy cost per year
	1100 Lumens	75 W $10.02/yr	53 W $7.08/yr	16 W $2.14/yr	15 W $2.00/yr	Energy use Energy cost per year
More bright	1600 Lumens	100 W $13.36/yr	72 W $9.62/yr	20 W $2.67/yr	19 W $2.54/yr (limited availability)	Energy use Energy cost per year
		1 year* Typical life	1–2 years Typical life	10 years Typical life	15–25+ years Typical life	

*Rated life is based on 3 hours of use per day

Fig. 44: Light bulb comparison in energy efficiency.
Source: BSE (2014)

Based on the above, it was determined that the most suitable light bulb for the purpose of the present work is the LED 5W, giving around 450 lumens and 12 Volts.

The next step was to calculate the current needed to light this light bulb, since it will determine the size of the device, purpose of this work.

As per Ohms law formula 3, the Power P [watts] is related to the Voltage V [volts] and current I [amperes].

Calculating the current with the actual voltage of 12 volts and 5 watts, the bulb draws 0,41A or 410mA to operate.

This means that whatever the power-generating device used (solar module or other device) to operate the light bulb, a current output of more than 400mA and a voltage of 12 Volts shall be generated.

6 CONCLUSION ANS PROPOSED WAY FORWARD

Based on the results of the test, the solution conceived in the form of a LED-based circuit is not feasible at this stage of the research, as the effort required to connect 44100 LEDs is not proportionate to the energy service provided (to lighten a bulb) as it would radically compromise the motivation of the work: find a practical and economical way to provide lighting to off-grid communities.

However, the effort undertaken is worth pursuing as one cannot satisfy herself with the status quo: the waste of electronic devices which should have a chance for a second life, without jeopardizing health and environment, and the fact that millions of people in developing countries still don't enjoy the basic energy service (lighten a bulb), compromising human development.

The work performed for the purpose of the present Master Thesis is an attempt to find ways to respond to the challenge. The generation of electricity with electronic waste is not without difficulties but achievable: regrettably the time available for the research and development work was too short considering the need for many more tests to make and other possibilities still open to research.

One important aspect of the idea was the 'home-made' character of the device coming from e-waste components, which can easily be mounted together following instructions. However, for the development itself of the device, more sophisticated tools would be required like indispensably an oscilloscope for the measurements: The current and voltage tested are in micro units and the oscilloscope is more accurate than a normal multimeter, which was used for the tests.

Promisingly, the amount of current generated with the circuit proposed in this thesis is sufficient to trigger a circuit, however at his stage it is not enough to light a bulb.

Some possible further developments and alternatives are presented hereunder.

Fresnel lens or magnifier could be used to increase the intensity of the light striking the pn junction, with the hope to increase the current output, but this is open for test. Fresnel lenses are easy to find in old TVs. A Magnifier (which may contain water or mineral oil for the purpose of amplifying) can possibly be made out of plastic bottle.

As an alternative system, a battery could be used to store the power generated by the original device during the day and in turn to power a light bulb when there is no sunlight. The self-made battery could be fabricated with common kitchen ingredients, along with copper and aluminum: experiments were done with copper as anode and aluminum as cathode and corn or potato starch, (corn and potato – starch are good conductors and have good electrical properties). The idea is that the original device (with the maximum power produced at this stage of the development) could charge the battery during the day generating the possibility to use the light bulb at night. However, tests need to be performed to determine the capacity and the size of the battery.

A test to lighten a blue LED was carried out with a self-made aluminum copper battery (3 cm X 1 cm in size), with potato starch between the junctions, connected to a small amplifier like the one described in the previous chapter. The blue LED kept lighting for 2 days, and the third day the light was to dim to be seen. Since no corrosion was noticed between the poles and the potato starch, it is worth investigating further the possibilities of this ecological battery.

Initially it was intended to compare the characteristic as well as the performance of the designed system with a single solar PV module. However the results of the tests performed at this stage render the comparison between both devices superfluous.

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LIST OF ABBREVIATIONS

Abbreviation	Description
AGECC	Advisory Group on Energy and Climate Change
AC	Alternating current
AREI	African Renewable Energy Initiative
A.C	After Christ
a-Si	Amorphous silicon
AM-0	Air Mass 0
AM-1,5	Air Mass 1,5
AlGaP	Aluminum Gallium Phospide
A	Ampere
BIPV	Building-integrated solar Photo Voltaic
B.C	Before Christ
BDM	Becker-DeGroot-Marschak
CdTe	Cadmium telluride
COP21	21st Conference of the Parties
CSP	Concentrated Solar Power
CIS	Copper indium diselenide
CdS	Cadmium sulfide
c-Si	Crystalline Silicon
DRE	Distributed Renewable Energy
DC	Direct Current
ESMAP	Energy Sector Management Assistance Program
e-waste	Electric and electronic waste
EnDev	Energizing Development
EDP	Energias de Portugal
EPIA	European Photovoltaic Industry Association
GaInN	Gallium Indium Nitride
GaAs	Gallium arsenide
GEA	Global Energy Assessment
GaAsP	Gallium arsenide phosphide
GaAsP:N	Gallium arsenide phosphide doped with Nitrogen
GaP	Gallium phosphide
GaN	Gallium nitride
Ga	Gallium
GW	Giga Watts
HH	Household
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
IFC	International Financial Corporation
IEA	International Energy Agency
IFC	International Finance Corporation
IBM	International Business Machines
I	Current
IZA	Institute for the Study of Labor
kWh	Kilo Watt hour
LiFi	Light Fidelity
LED	Light Emitting diode
lm	Lumens
MW	Mega Watts
mA	Milliampere

Max	Maximum
mm	Millimetres
NASA	National Aeronautics and Space Administration
N junction	Negative Junction
NPN transistor	Negative, Positive, Negative transistor
nm	Nanometer
OECD	Organization for Economic Co-operation and Development
OPIC	Overseas Private Investment Corporation
PAYG	Pay As You Go
PV	Photovoltaic
PIDG	Private Infrastructure Development Group
P junction	Positive Junction
PCB	Printed Circuit Boards
P	Power
REN21	Renewable Energy Policy Network for 21st Century
R&D	Research and development
RISE	Regulatory Indicators for Sustainable Energy
RGB	Red Green Blue
SE4All	Sustainable Energy for All
SHS	Solar home systems
SiC	Silicon Carbide
SMT	Surface-mount technology
TED Global Talk	Technology, Entertainment and Design Global Talk
TES	Thermal Energy Storage
UNDP	United Nations Development program
UN	United Nations

USD	United States Dollar
UNEP	United Nations Environment Program
UNODC	United Nations Office on Drugs and Crime
USAID	United States Agency for International Development
uA	Microampere
VAT	Value-added tax
V	Volts
WP	Watt Pico
WCO	World Customs Organization
WTP	Willingness to Pay

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