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## ► To cite this version:

Benjamin Pillot, Marc Muselli, Philippe Poggi, João Batista Dias. On the impact of the global energy policy framework on the development and sustainability of renewable power systems in Sub-Saharan Africa: the case of solar PV. 2016. hal-01502002

**HAL Id: hal-01502002**

**<https://hal.science/hal-01502002>**

Preprint submitted on 4 Apr 2017

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# On the impact of the global energy policy framework on the development and sustainability of renewable power systems in Sub-Saharan Africa: the case of solar PV

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## Abstract

From 1972 and the *Meadows* report to 1997 and the ratification of the Kyoto Protocol by most of the countries in the world, the global energy policy framework has undergone a paradigm shift, as human societies have been leaving aside the sole economic growth to embrace the broader concept of *sustainable development*. As new electrification vectors, modern renewable power systems, such as solar PV, have sprung up in the wake of this major mutation and have typically been following an exponential growth since the mid-nineties. Electricity as well as its lack indeed holds a central position within the *human development* apparatus, from highly interconnected centralized power networks reaching 100 % of the population in developed countries, to the almost 500 millions people without access to electricity in the multidimensionally poor rural areas of Sub-Saharan Africa. The encounter of the worldwide energy context being changed with each of these specific *social-energy* paradigms has ended up considering two strategies for integrating renewable resources in power systems: the *grid-connected* architecture for meeting the sustainable development requirements, and the rural *off-grid* electrification for settling the lack of human development. By means of a historical and cross-sectional overview, we depict here the ins and outs of this protean pattern and, using the case of solar PV, analyze how it has eventually affected the development and sustainability of renewable power systems in Sub-Saharan Africa.

**Keywords:** Sub-Saharan Africa; solar PV; sustainable development; human development; off-grid electrification; grid-connected

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## Words:

- Words in text = 9905
- Words in headers = 267
- Words outside text (captions, etc.) = 340

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## 1. Introduction

Energy and human development have been strongly correlated since the beginnings of time, and this assertion has become particularly true with the industrial era. The first industrialized countries in history have thus reached the highest level of human development and remain, at the present time, the largest consumers of energy per capita in the world [1, 2]. Unfortunately, this evolution of the primary energy consumption, especially for sustaining the economic growth, which can be regarded as the *quantitative* part of the human development [3, 4], has led to 2 main worldwide issues, that is exhaustion of the fossil fuel resources and global warming resulting from greenhouse gas (GHG) emissions.

The first oil shock in the seventies has raised the awareness of the developed countries about both these issues, outlined by the 1972 Meadows report about *The limits to growth* [5]. The need of alternatives to petroleum, of a more efficient energy sector, of long-term energy policies or of an environmental approach to energy has become manifest to them [6]. As a result, they have elaborated an international policy framework in order to meet these new goals, with at first the establishment of the International Energy Agency (IEA) in 1974 currently composed of 28 developed countries<sup>1</sup> plus Turkey [6, 7]. This policy framework has then evolved with the increasing of the realization about the significant impact of economic development, along several key dates such as: 1983 and the designation of a World Commission about environment and development; 1987 and the Brundtland report defining the *sustainable development* concept [8]; 1992 and the *Earth Summit* mainly resulting in a convention on climate change [9]; 1997 and the Kyoto Protocol, the first international treaty inciting the industrialized countries to fight global warming by reducing their GHG emissions [10]. Accordingly, in order to overcome the world energy issue coupling fuel resource exhaustion and global warming, this specific policy framework has directly and indirectly been supporting the use of renewable energies for more than 40 years, but more significantly since the Kyoto Protocol [10, 11].

Among all types of energy, electricity has more particularly defined modern life as we know it today, and is a very good marker of the level of development populations have reached [12, 13]. Many developing countries currently have really low electrification rates in comparison with the universal access to electricity of developed countries [14, 15]. Within this context, rural areas of the developing countries are the most affected, especially in Sub-Saharan Africa<sup>2</sup>, where more than 80 % of the rural dwellers, that is 500 million people, are presently living without any electricity supply [13, 14, 16]. Accordingly, rural electrification has become a key parameter of the poverty reduction world policy [13, 17]; among the different approaches proposed to meet this goal, the use of renewable power systems has been increasingly considered over the last 30 years [13, 15]. However, in Sub-Saharan Africa, power supply capacity per capita has not increased since the eighties and the electrification rate still remains dramatically low [3, 14]. On the other hand, many of the renewable systems currently used for off-grid rural electrification in developing countries also present sustainability and development issues [15, 18].

At the present time, the solar potential is really substantial in Sub-Saharan Africa [19, 20], which probably explains why, except traditional biomass, use of solar energy in rural areas is both more supported politically [21, 22] and prevailing

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<sup>1</sup>According to the United Nations definition (see section 3.1)

<sup>2</sup>Here we consider Sub-Saharan Africa referring to all of Africa except the following countries: Algeria, Egypt, Libya, Morocco, Western Sahara, and Tunisia.

32 among field applications [23, 24] than any other renewable resources. In the same way, photovoltaics (PV) is also the most  
33 promoted technology for electrifying rural people across the sub-continent, especially through solar home (SHS) and solar  
34 pico systems (SPS) [23, 24]. However, the development of the sector is still in its beginning in Sub-Saharan Africa, with an  
35 effective installed capacity remaining low [24, 25], and, like other renewable power systems in developing countries [15], field  
36 applications employed in off-grid electrification show the same sustainability issues [23, 26, 27].

37 May this state of affairs partially be the consequence of the aforementioned world energy policy paragon set up by the  
38 developed countries, from the first appearance of the sustainable development concept to the current renewable energy policies  
39 derived from the Kyoto Protocol targets ? The thesis defended by the authors is indeed that the last 30 years of development in  
40 the renewable energy field have mainly been driven by one model, as a result of the global energy frame commitments coupled  
41 with the specific power supply structure of the developed countries, and that eventually this latter has negatively influenced  
42 the success of implementing renewable power systems in Sub-Saharan Africa. In order to understand the essence of this  
43 framework and how it has potentially impacted both the development and sustainability of the renewable energy projects in  
44 the region, we have achieved:

- 45 • an historical and cross-sectional overview of the global energy context, that is a comparative analysis of the ins and outs  
46 of the 2 different *social-energy*<sup>3</sup> paradigms involved, in order to apprehend the characterization of electricity supply  
47 and renewable power systems accordingly. From the need of *sustainable development* to developing *grid-connected*  
48 facilities on the one hand; from the lack of *human development* to implementing rural *off-grid* electrification on the  
49 other (section 2 to section 4);
- 50 • a comprehensive description of the resulting impact of this pattern by focusing on the solar PV technology (section 5);

## 51 2. Global energy policy framework

52 The current worldwide energy policy framework has a history whose the origin can probably be dated to the dawn of the  
53 seventies. It is rooted in the first oil shock and the related contemporary realization about the finiteness of the resources and  
54 the consequences of economic development, embodied by the *Meadows* report<sup>4</sup>.

### 55 2.1. Current energy situation

56 Today, the global energy situation can be described as a crossing between two main issues: depletion of fossil resources  
57 and global warming due to greenhouse gas (GHG) emissions. The first one is related to the exhaustion of fossil fuels such  
58 as oil, coal, gas or uranium required to ensure operating of the classical energy supply systems. Reserves of these resources  
59 are indeed limited in time and decrease as fast as the world energy consumption increases. Table 1 depicts the current proved  
60 reserves of the main fossil fuels using the reserves to production ratio, which is an estimate of their lifetime according to the  
61 current energy consumption.

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<sup>3</sup>The *social-energy* term features here the two-way interaction existing between energy and social frameworks, and emphasized in sections 3 and 4.

<sup>4</sup>Though this report is probably the most well-known, it is important to cite the other founder, and more theoretical, work released by the economist Georgescu-Roegen one year before: *The entropy law and the economic process* [28].

Table 1: Proved reserves of fossil fuels in 2013 [29, 30]

Fossil fuel	Reserves to Production ratio
Oil	53.3 years
Coal	111.2 years
Natural gas	55.1 years
Uranium*	128.3 years

\* Reasonably assured resources + inferred resources

62 This significant consumption of energy resources can be regarded as one of the main causes of the second issue, that is  
 63 global warming. Except for nuclear energy, fuel combustion in the energy field is indeed the largest source of greenhouse  
 64 gases (GHG), with almost 70 % of the global emissions, mainly consisting of carbon dioxide [4]. This unnatural growth of  
 65 the natural greenhouse effect has led to an increase of the average Earth's temperature [31], and so to a sustainable change  
 66 of the climate. Over the past 30 years, the world temperature has thus increased significantly [32], while the atmospheric  
 67 concentration of anthropogenic GHG (carbon dioxide, methane and nitrous oxide) has been growing dramatically, as depicted  
 68 in Figure 1. At the present time, this relation between growth of the human industrial activity and global warming appears  
 69 very consistent [31], and so is almost unanimously admitted within the climate scientific community [33].

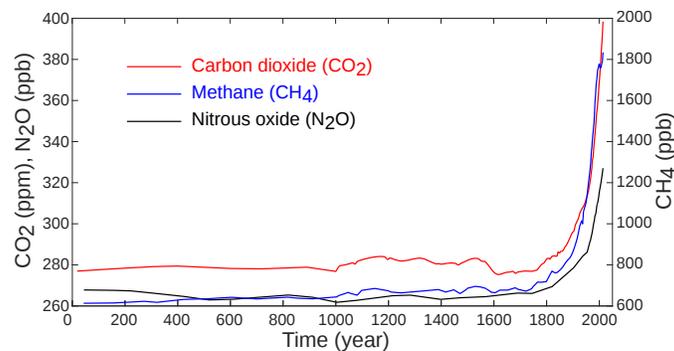


Figure 1: Atmospheric concentration of the major anthropogenic greenhouse gases over the last 2000 years [34, 35], in parts per million (ppm) and parts per billion (ppb).

70 It is within this specific questioning about human development issues that emerged, in the 1970s, new energy alternatives  
 71 and the concept of *sustainable development*.

## 72 2.2. Advent of the sustainable development and rise of the renewable energies

73 The first oil shock in 1973 was the start of a growing realization by the international community of the significance of the  
 74 energy challenges in the mankind's future development. Beyond the Club of Rome's report, entitled *The limits to growth* [5],

75 published in 1972, or the first international conference about environment which took place in Stockholm the same year [36],  
 76 appears a more global questioning about the consequences of the lifestyle of the industrialized countries.

77 *2.2.1. Emergence of the sustainable development concept*

78 The following step of this self-questioning was the designation in 1983, by the General Assembly of the United Nations  
 79 (UN), of a World Commission on Environment and Development headed by Gro Harlem Brundtland. The report published by  
 80 this commission in 1987, and entitled *Our common future*, established in the first place the concept of *sustainable development*,  
 81 defined as a development “seeking to meet the needs and aspirations of the present without compromising the ability to meet  
 82 those of the future” [8]. Typically, this development is a balance between social, economic and environment features, so as to  
 83 preserve the environment, the equity between peoples, persons and generations, and the economic efficiency [36]. Thereafter,  
 84 the Brundtland report was the base of the United Nations Conference on Environment and Development (UNCED), known as  
 85 the *Earth Summit*, which took place in Rio de Janeiro in 1992 [36]. The United Nations Framework Convention on Climate  
 86 Change (UNFCCC) adopted during this summit [9] served then as a frame to the establishment and ratification of the Kyoto  
 87 Protocol in 1997 [10]. The main purpose of this protocol, which has been ratified by 191 countries [37], was to make 37  
 88 industrialized countries and the European Community (*Annex I countries*) reducing their GHG emissions (Article 3), in order  
 89 to promote sustainable development (Article 2). Accordingly, it has directly and indirectly encouraged these countries to look  
 90 for alternative solutions in order to cut back their emissions, either by limiting their energy consumption or by replacing their  
 91 current energy supply systems by lower emitter ones.

92 *2.2.2. Renewable energies*

93 Unlike fossil fuels, renewable energies are almost unlimited, at geological time scale, and carbon-free energy supply  
 94 solutions. Indeed, these energies mainly come from the sun, directly or indirectly (direct solar, biomass, hydro, wind and  
 95 wave energies), but also from the Earth’s core high temperature (geothermal energy) and the Earth-Moon-Sun gravitational  
 96 system (tide) [38, 39]. Table 2 summarizes both the type and the yearly potential of each renewable resource. In addition,  
 97 compared to the yearly world total primary energy supply ( $155.5 \times 10^{12}$  kWh), this table also shows that the annual renewable  
 98 energy reserves are particularly significant, even if only a small part can really be exploited [38, 40].

Table 2: Estimated yearly potential of renewable resources [38].

	Sun	Biomass	Water cycle (hydro, wind, wave)	Geothermal	Tide
Yearly potential (kWh)	$700 \times 10^{15}$	$4.5 \times 10^{15}$	$360 \times 10^{15}$	$300 \times 10^{12}$	$25 \times 10^{12}$

99 The second aspect differentiating renewable resources from fossil fuels is the amount of GHG emissions, especially of  
 100 CO<sub>2</sub>. In the case of the biomass, the fuel cycle is considered neutral, that is the CO<sub>2</sub> released during the resource combustion

101 is counterbalanced by the CO<sub>2</sub> absorbed during its growth [14]. For the other resources, they are either used directly or  
 102 converted using systems which are not CO<sub>2</sub> emitters apart from the one indirectly released (manufacturing, transport, etc.).  
 103 Table 3 depicts the life cycle CO<sub>2</sub> emission rates of different power systems using fossil or renewable resources. Emissions of  
 104 both these resources are significantly different, the emission rate being 10 to 20 times larger for fossil fuels than for renewable  
 105 energies. Besides, the case of the nuclear energy remains particular since, despite low emissions, it presents other issues such  
 106 as radioactive waste and installation safety.

Table 3: Life cycle CO<sub>2</sub> emissions of fossil and renewable power generation, according to the Japanese example [41].

	Power generation	CO <sub>2</sub> emissions (gCO <sub>2</sub> /kWh)
Fossil fuels	Nuclear	24.2
	Gas/combined cycle	518.8
	Gas/fired	607.6
	Oil	742.1
	Coal	975.2
Renewable systems	Hydro	11.3
	Geothermal	15.0
	Wind	29.5
	Photovoltaics	53.4

107 Hence, the renewable energies present inherent characteristics providing prospective solutions for the current world energy  
 108 issues. Unlike fossil fuels, renewable resources are inexhaustible and converted through more ecological energy systems, and  
 109 their reserves remain substantial enough for coping with the growth of the world population and so of the energy needs in the  
 110 future.

### 111 2.2.3. Sustainable development policy framework and new rise of the renewable energies

112 As described previously, renewable resources present two main features directly related to the two issues of the global  
 113 energy context, that is unlimited reserves and low GHG emissions allowing mitigation of both fossil fuel depletion and global  
 114 warming effects. As a result, they have legitimately become one of the spearheads of the new main global energy policy.

115 The Kyoto Protocol has directly encouraged the Annex I countries to take into consideration renewable energies; indeed,  
 116 the section 1.(a).(iv) of the article 2 recommends the “research on, and promotion, development and increased use of, new  
 117 and renewable forms of energy” [10]. As a result, if all national renewable energy policies have been implemented after 1973,  
 118 as a direct consequence of the first oil shock, about 95 % and 90 % of these policy measures have followed the establishment  
 119 of the UNFCCC and the Protocol, respectively [11]. These incentive policies have essentially been relying on financial

120 (public and private funding), fiscal (tax exemptions, environmental taxes), legislative (power purchase, grid access), political  
 121 (penetration level targets, support programs) or technological and environmental support (R&D program funding, Carbon  
 122 Footprint concept) [42]. In that way, even if hydro and geothermal energies were already used or considered at the end  
 123 of the 19th century for producing electricity [43–45], the emergence of the sustainable development, and thereafter of the  
 124 corresponding energy policy framework (UNFCCC and Kyoto Protocol), has strongly fostered the new<sup>5</sup> rise of the renewable  
 125 energies.

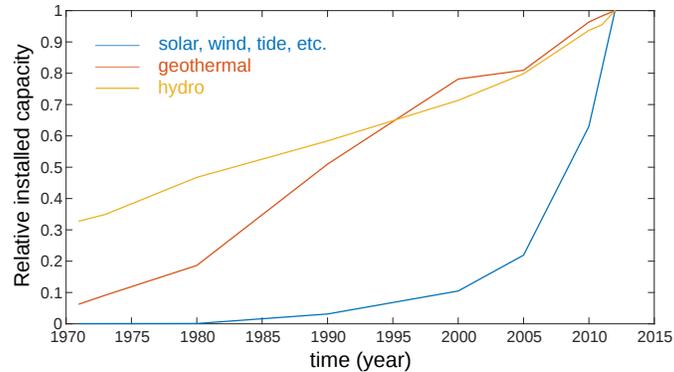


Figure 2: Evolution of the renewable energy installed capacity over the past 40 years, for each technology [40].

126 Accordingly, since the 1970s, hydro energy generation has tripled, geothermal energy has been multiplied by 16 and  
 127 production of energy from solar, wind, tide and other types has grown by almost a factor 2000 [40]. Above all, the analysis  
 128 of the evolution of these *modern* renewable energies (solar, wind, tide, etc.), i.e. energies with no installed capacity before  
 129 the 1970s, shows the significant role the energy policy framework has played in their development. Figure 2 depicts, for  
 130 each renewable technology, the evolution of the relative installed power over the past 40 years, i.e. the ratio between the  
 131 installed capacity at the time and the one corresponding to the current year (2012). If hydro and geothermal energies have  
 132 approximately followed a linear increase, installed capacity of other renewable energies really sprung up in the 1980s and has  
 133 had an exponential growth until now, with the incline getting significant at the beginning of the years 2000, that is after the  
 134 establishment of the UNFCCC and the Kyoto Protocol.

### 135 3. Electricity and development

136 Overall, development cannot be achieved without energy [3]. Total primary energy supply has thus grown more than  
 137 twice in 40 years, mainly for supplying the economic growth [4]. Within this specific paradigm, electricity mainly ensures  
 138 enhancement of the qualitative criteria of the *human development*.

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<sup>5</sup>Since mankind has firstly used renewable resources in its history (mills, sailboats, agriculture, etc.), we consider *new* the use of these energies after the Industrial Revolution.

139 3.1. Human development and multidimensional poverty

140 Today, the level of development of a country is defined by its human development index (HDI), ranging from 0 to 1,  
141 which is yearly calculated for more than 20 years by the United Nations Development Programme (UNDP) [46]. *Human*  
142 *development* was originally defined by Mahbub ul Haq [47] as the growing process of both the choices available to the  
143 populations and the degree of well-being they have reached. In theory, these choices are infinite, but, in practice, some of  
144 them can be considered fundamentals since they allow access to all the other ones, that is having a long and healthy life,  
145 acquiring knowledge and getting enough resources for a decent standard of living [47]. The HDI is therefore computed from  
146 3 indices assessing the level of quality of each of these criteria, that is health, education and income: the life expectancy index  
147 (based on the life expectancy at birth), the education index (based on the mean and expected time of schooling) and the gross  
148 national income (GNI) index (based on the GNI per capita).

149 The HDI was defined for 187 countries in 2013 [46], divided into 4 quartiles corresponding to very high ( $HDI \geq 0.808$ ),  
150 high ( $0.700 \leq HDI \leq 0.790$ ), medium ( $0.556 \leq HDI \leq 0.698$ ) and low human development ( $0.337 \leq HDI \leq 0.540$ ),  
151 respectively. Typically, the countries having a very high human development are considered *developed* while all the other  
152 ones are regarded as *developing*<sup>6</sup> [46]. Furthermore, although no official status exists for the most developed countries, one  
153 has nevertheless been attributed by the UN to 48 countries presenting the lowest HDI, known as the least developed countries  
154 (LDCs) [49]. With 33 out of 49 countries being part of the LDCs, Sub-Saharan Africa is by far the least developed region in  
155 the world [46].

156 Moreover, for the least developed regions, it is also interesting to analyze the complement of the human development,  
157 that is the multidimensional poverty [50], and its corresponding index, the multidimensional poverty index (MPI). If the HDI  
158 gives a global outlook of the level of development in a country, the MPI also indicates the part of the population suffering  
159 from deprivations and the intensity of these deprivations, in the same 3 dimensions (health, education and standard of living).  
160 Consistently, the MPI tends to increase when the HDI decreases, which means that human development must firstly rely  
161 on mitigation of the multidimensional poverty, especially when it affects most of the people such as in Sub-Saharan Africa,  
162 where more than 50 % of the population is currently multidimensionally poor [50]. The 3 dimensions of the MPI are equally  
163 weighted, and are based on 10 indicators, corresponding to deprivation thresholds, distributed as follow [50]:

- 164 • 2 health thresholds related to having at least one household member who is malnourished and one or more children who  
165 have died;
- 166 • 2 education thresholds related to having at least one school-age child not attending school and no household member  
167 who has completed 5 years of schooling;
- 168 • 6 standard of living thresholds related to not having electricity, not having access to clean drinking water, not having  
169 access to adequate sanitation, using “dirty” cooking fuel (like wood or charcoal), having a home with a dirt floor, and  
170 owning a limited number of goods.

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<sup>6</sup>The UN definition is different and considers the level of development in a geographical way, so that only Europe, Northern America, Japan and Australia/New Zealand are regarded as developed countries [48].

171 3.2. *Electricity in modern societies*

172 Among all energies, electricity is probably the most representative of the level of development of a country, and its advent  
173 at the end of the 19th century deeply changed the world behavior [43]. Energy supply per capita increased over the centuries  
174 with the technology intended to simplify the human daily activities; but electricity definitely allowed the rise of the *modern*  
175 *era*.

176 As a matter of fact, electricity coupled with alternating current has provided a *clean* and easy-to-use energy where it is  
177 consumed, and so has contributed to the current modern life. As a result, if electricity was about 2 % of the final energy in  
178 1940, this share is now more than 18 % and steadily increasing [38, 40]. Most of the devices (air conditioner, refrigerator,  
179 computer, etc.) and basic services (clean water, medical care, means of information and communication, etc.) making life  
180 more comfortable are now fueled by electricity [43].

181 3.3. *Access to electricity: a rural issue*

182 If electricity allowed modernization of life in the rich countries, the access to that energy currently remains particularly  
183 disparate in the world, the electrification rate being strongly dependent on the level of development of each region.

184 In 2012, the electrification rate of the more developed regions was about 100.0 % against 76.3 % for the developing  
185 countries [14]. Worldwide, it was almost 1.3 billion of people without any access to electricity. Also, in order to better  
186 understand the issue in developing countries, it is relevant to analyze the population distribution between urban and rural  
187 areas. Indeed, in 2012, urbanization rate of the more developed regions was 77.6 %, while it was equal to 47.3 % in developing  
188 countries [48]. Among them, only 29.9 % and 36.3 % of the people in LDCs and Sub-Saharan Africa, respectively, were living  
189 in urban areas. Essentially, more than 3 billion people are currently living in rural areas, and the linking of this social feature  
190 with the electrification rate highlights that, at the present time, about 83.6 % of the people without access to electricity are  
191 living in rural areas.

192 Table 4 summarizes this specific context, with global, rural and urban electrification rate, as well as the urbanization rate,  
193 for each region of the world. In developing countries, we can note that the access to electricity decreases while the proportion  
194 of people living in rural areas grows. Besides, with an electrification rate of 32 % and a power supply capacity per capita  
195 still identical to the 1980s [3], Sub-Saharan Africa remains the least electrified region in the world. With 486 million people  
196 without access to electricity, the rural electrification rate of the region (16.6 %) is dramatically low, far behind the developing  
197 countries taken as a whole (64 %).

198 3.4. *Electrification as a vector of the human development*

199 3.4.1. *HDI vs access to electricity*

200 Table 4 already gave an indication about the relationship between level of development and access to electricity. Indeed,  
201 enhancement of the life conditions in many countries, i.e. increasing their HDI, would require increasing their electricity  
202 consumption by a factor 10 or more [12]. Using values from 2012<sup>7</sup> and according to the example of Hegedus and Luque

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<sup>7</sup>Most recent available year for electricity consumption.

Table 4: Access to electricity in 2012 [14, 48].

Region	Urbanization rate (%)	Electrification rate (%)	Urban electrification rate (%)	Rural electrification rate (%)
<b>More developed regions<sup>1</sup></b>	<b>77.6</b>	<b>100.0</b>	<b>100.0</b>	<b>100.0</b>
Japan	91.9	100.0	100.0	100.0
Australia/New Zealand	88.6	100.0	100.0	100.0
Northern America	81.1	100.0	100.0	100.0
Europe	73.0	100.0	100.0	100.0
<b>Developing countries<sup>1</sup></b>	<b>47.3</b>	<b>76.3</b>	<b>91.1</b>	<b>64.0</b>
Latin America	79.0	95.0	98.5	81.9
Middle East	69.0	91.7	98.3	78.0
Developing Asia <sup>2</sup>	43.5	83.0	95.2	74.4
Africa	39.2	42.5	68.0	25.6
<i>Sub-Saharan Africa</i>	<i>36.3</i>	<i>32.0</i>	<i>59.2</i>	<i>16.6</i>
<b>World</b>	<b>52.6</b>	<b>81.7</b>	<b>94.1</b>	<b>68.0</b>

<sup>1</sup> According to the UN geographic definition.

<sup>2</sup> Corresponding to Asia without Middle East and Japan.

203 [12], Figure 3 illustrates this strong correlation existing between consumption of electricity and quality of life by plotting HDI  
 204 versus electricity consumption per capita.

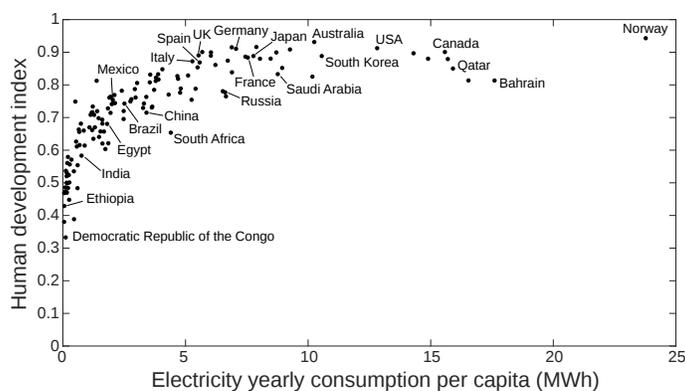


Figure 3: HDI vs. electricity consumption [2, 40, 46].

#### 205 3.4.2. *Effects of electricity on MPI components*

206 In order to understand how electricity access can enhance human development in the LDCs, and so in Sub-Saharan Africa,  
207 it is relevant to look at how it can remove the different deprivations in the 3 MPI dimensions. As a matter of fact, lack of  
208 electricity is more significant for people who are multidimensionally poor, and Sub-Saharan Africa remains the most affected  
209 region, with more than 60 % of the poor living without any access to it [3, 50]. Impact of a future electrification can be  
210 evaluated by analyzing the current issues the lack of electricity brings out, directly or indirectly assessed by the MPI, as well  
211 as the experiments conducted in different developing countries [3, 43, 51].

212 By looking at every deprivation threshold, we can note that access to electricity is a critical criterion. It can contribute to  
213 the use of cleaner cooking fuels, especially for preventing diseases deriving from solid fuel combustion smoke [52], to improve  
214 the access to clean water (pumping and filtering), to run some devices making life more comfortable. Regarding education,  
215 effects are either direct, such as the lack of individual or public lighting which restrains the available time for studying [51, 53];  
216 or indirect, with for example the time spent by children to collect water or cooking fuel which slows down academic progress  
217 and mitigates schooling rate, especially for the girls. In rural areas of Malawi, for example, they averagely dedicate about 4  
218 hours per week for fetching water and wood, against 3 times less for the boys [3]. On the subject of health care, many modern  
219 devices and services (clean water, vaccine storage), which help to prevent child mortality, require electricity to operate, bad  
220 nutrition may partially result from inadequate cooking systems, the use of conventional energy resources and traditional light  
221 sources can decrease the air quality, and fuel fetching in difficult environments can be physically harmful [3, 53].

222 Initiatives against poverty in some developing countries also highlight the multidimensional positive influence of electricity  
223 on development, such as projects carried out by Rodrigo Baggio and Fabio Rosa in Brazil, or by Sanjit Bunker Roy in India.  
224 Baggio has democratized computer tools for young people in the favelas of Rio de Janeiro; Rosa has developed a solar panel  
225 rental company in Porto Alegre for rural people (fence electrification, irrigation, etc.); and Bunker Roy acts for education in  
226 rural areas of India, especially by using PV lighting to get schools up and running at night [54].

#### 227 3.4.3. *Electricity and the qualitative part of human development*

228 As depicted previously, direct and indirect influences of electricity on the poverty dimensions are particularly significant.  
229 In addition, we can note that GHG emissions and primary energy supply are more correlated to the economic growth than  
230 to the evolution of the health and education criteria of the human development [3, 4]. As a matter of fact, as shown by  
231 Klugman [3], it is intuitively understandable that these fields first rely on a *qualitative* use of energy, that is supplying energy  
232 for allowing services such as schools and hospitals to operate; on the contrary, the economic growth mainly relies on the  
233 manufacturing of goods and thus on a *quantitative* use of energy. Considering the aforementioned relationship with reduction  
234 of multidimensional poverty, access to electricity therefore implies, in the first stages, enhancing the qualitative dimensions of  
235 the human development (health, education, life comfort), resulting *de facto* in limited impact on GHG emissions and resource  
236 exhaustion.

237 3.5. *The rural issue in Sub-Saharan Africa*

238 Regarding power supply, if Table 4 confirms that the least developed regions in the world have the lowest electrification  
239 rates, it also highlights the significant disparities existing between rural and urban areas. Sub-Saharan Africa is an accurate  
240 picture of this issue since, with 486 million people, it is more than one third of the world population without access to  
241 electricity which is living in the rural areas of the region.

242 More than 60 % of the Sub-Saharan African population is currently living in rural areas, and projections show this preva-  
243 lence is not likely to be reversed before 2040 [55]. Since human development is really low in most of the Sub-Saharan  
244 countries (33 are regarded as LDCs), rural populations are much more subject to poverty issues as they remain distant from  
245 the urban centers. As a matter of fact, in addition to global poverty, these populations also suffer from living in under-served  
246 remote areas [56], which is especially apparent concerning electricity network and transport infrastructures. The first one has  
247 already been emphasized with the low rural electrification rate (16.6 %); the second aspect is related to the very sparse road  
248 network, which consists of only 18 % paved roads, making the accessibility very low in the region, that is significant travel  
249 time to major cities [57], and so any kind of supply (energy, material, etc.) is really tricky to achieve [58]. Furthermore,  
250 infrastructural access to basic services, such as water supply or medical care, is also insufficient and more substantial in urban  
251 areas: access rates to improved sanitation facilities and improved water supply are respectively equal to 24 % and 40 % in  
252 rural areas, against 43 % and 82 % in urban areas [58].

253 Inadequacy of electricity and transport networks makes the access to *modern* fuels really difficult [3], and incites people  
254 from rural areas to look for resources located in their close environment. As a result, in Sub-Saharan Africa, these populations  
255 mostly use fuelwood as energy supply [21], especially for cooking with nearly 730 million people (80 %) still relying on the  
256 traditional use of solid biomass [14]. Depending on the context, this energy use alongside other kind of forestry and pastoral  
257 activities, such as cash crops, wood exportation or bushfires [59], can harm the surrounding environment significantly and  
258 therefore imply severe socioeconomic troubles for the populations [21]. In this way, when the resulting local deforestation  
259 or desertification don't allow resources to be renewed anymore, these populations are then forced into rural flight [3]. Most  
260 often, they join the nearest urban centers, whose some of them like Timbuktu in Mali or Agadez in Niger have quadrupled  
261 their population in 30 years [59]. As the polish author Ryszard Kapuściński once wrote [60]: “[these people] do not come  
262 here because the city needs them, but because poverty has driven them out from their village”. Finally, as urban centers also  
263 suffer from poverty and lack of infrastructures, they are not able to absorb this significant inflow, so these populations mostly  
264 come growing suburban slums and informal settlements, which makes human development still harder to enhance [56, 61].

265 Figure 4 summarizes this aggravated socioeconomic situation of rural people in Sub-Saharan Africa, by describing the  
266 increase of the number of people affected by multidimensional poverty (MPI headcount) with the rural population of a country.  
267 The almost linear evolution between both these criteria indicates the strong likelihood for an individual living in rural areas of  
268 Sub-Saharan Africa to be multidimensionally poor.

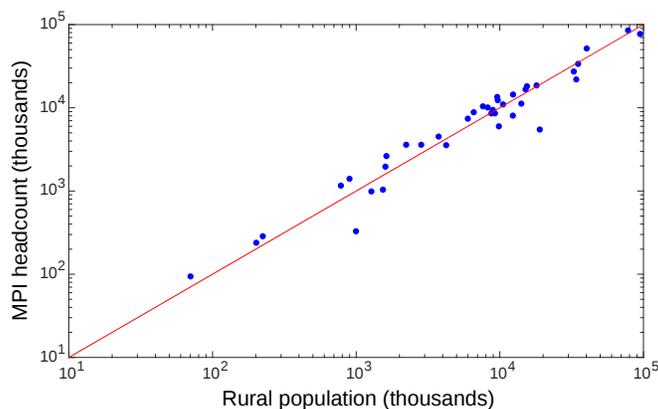


Figure 4: Evolution of the MPI headcount with the rural population in Sub-Saharan countries [46, 48].

## 269 4. Electrification paradigms and renewable energies

270 If energy has social implications, social structures also imply looking for suitable energy supply models; this influence  
 271 of the one on the other allows us to speak of *social-energy* issue. In the case of electricity, the rural context of Sub-Saharan  
 272 Africa has led to a new major approach: the off-grid electrification.

### 273 4.1. Centralized electrical networks

274 Electricity was originally expensive, difficult to carry over long distances, and had to be directly consumed since storage  
 275 was technically hard to achieve [43]. Alternating current (AC), by making electricity transmission technically and econom-  
 276 ically feasible, and interconnection, by ensuring the distribution of electricity without requiring any storage, have enabled  
 277 to overcome these limits. By aggregating consumption and production hazards and using complementarity between power  
 278 systems, interconnection has enhanced the reliability of the supply and reduced both the margins of safety and the fuel con-  
 279 sumption of power plants [44]. Hence, the more powerful and interconnected a power station is, the more reliable and  
 280 economical it will be (*returns to scale* phenomenon); combined with AC use, it has then led to the actual *centralized* structure  
 281 of electrical grids [39, 44].

282 A centralized grid is a large-scale power system carrying electricity from power stations to consumption sites (loads),  
 283 through *transmission* and *distribution* networks, ensuring both transformation of electricity with respect to the consumer  
 284 needs and permanent balance between production and consumption [62]. Power plants are connected to the transmission  
 285 network (extra high and high voltage), while energy is delivered to the consumers through the distribution network (medium  
 286 and low voltage). Figure 5 describes the structure of such a network using the UK voltage example [39]. The transmission  
 287 network (400 kV and 132 kV) carries electricity provided by power plants over long distances, while the distribution grid (33  
 288 kV, 11 kV and 400/230 V) supplies consumers in smaller areas.

289 *Urban areas* stand here for the high urbanization rate of fully electrified regions combined with the electrification process  
 290 history. In fact, in the beginnings, *pseudo urbanization* followed the primary expansion of electrical grids, in a phenomenon

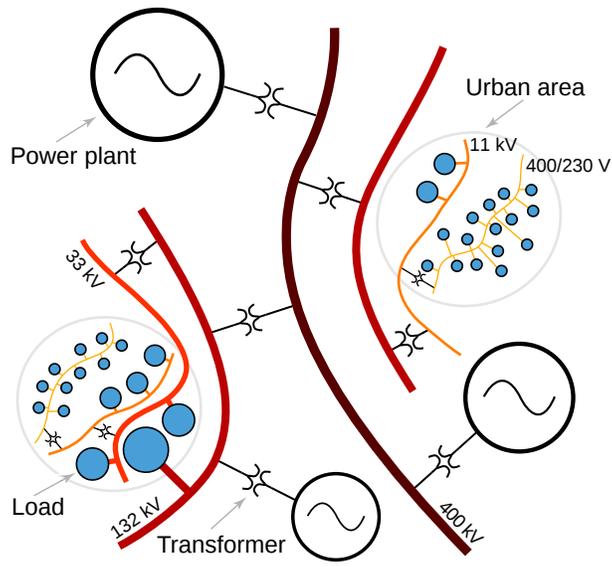


Figure 5: Centralized grid, according to the UK example [39].

291 known as *pre-electrification*, as remote people was attracted to larger population centers [43]. This aggregation of the rural  
 292 consumers allowed a critical load threshold to be reached, making the interconnected power system expansion in these areas  
 293 economically relevant [43, 63].

#### 294 4.2. Off-grid electrification and human development in Sub-Saharan rural areas

295 In Sub-Saharan Africa, electricity supply can enhance human development of populations mainly located in rural areas,  
 296 by mitigating multidimensional poverty, that is reducing deprivations and rural flight into urban slums. Electricity supply of  
 297 these remote areas is currently almost non-existent, while urban electrification rate remains really low in the region, at 59.2%,  
 298 against more than 95% in the other developing regions (Table 4). Moreover, not only many Sub-Saharan countries have faced  
 299 recurrent power crisis over the last years, pointing out the persistent decline of their centralized networks [64] and the lack  
 300 of reliable power infrastructures [65], but extending a network also requires proper load factors, and so enough gathering of  
 301 population, to be economically viable [63, 66, 67]. As a result, these countries are likely more concerned at the present time  
 302 with improving current grids and power infrastructures than about expanding it so as to reach small, remote and scattered rural  
 303 areas, which appear on top of that economically less relevant than urban areas [13].

304 The current promoted idea for suiting the electricity needs of these populations can be defined, according to Huacuz and  
 305 Gunaratne [43], as the change of the electrification model from a centralized grid *delivering electricity to rural areas* to a  
 306 structure which allows *increasing the access of the rural people to electricity*. The corresponding pattern is known as *off-grid*  
 307 *electrification*: providing electricity where it is consumed using small-scale and suited to the needs stand-alone power systems  
 308 [1, 13, 43, 53, 68, 69]. Essentially, a centralized grid is a global power system mesh to which any consumer can connect,  
 309 while off-grid electrification can be seen as a local customization of the power systems meeting the needs of every consumer.

### 310 4.3. Renewable energies in power systems

311 Depending on the electrification paradigm, the use and integration of renewable systems in the energy scheme is different.  
312 On the one hand, it means adapting the inherent intermittency and low capacity factors to the grid requirements, and on the  
313 other hand, meeting the local needs using small-scale and mixed power systems.

#### 314 4.3.1. Renewable energies in centralized power systems: grid-connected systems

315 Because of their inherent features, integration of renewable energies in modern centralized grids presents some significant  
316 challenges. Firstly, unlike fossil fuel based power systems, renewable energies such as wind and solar present significant  
317 geographical scattering, and so often require small-scale conversion systems [38]. Therefore, most of the renewable power  
318 stations have to be directly connected onto the distribution network (*decentralized production*) rather than onto the transmis-  
319 sion system as usual [39, 70]. Secondly, most of the renewable energies, including wind, solar, wave and tide energies, are  
320 *intermittent*, because of climate features, meteorological phenomenons, geographical location or day-night alternation. This  
321 intermittency makes variable renewable energy systems have low capacity factors (variability) and causes temporal mismatch  
322 between demand and supply within the grid (uncertainty). As a result, integration of variable renewable energies require grid  
323 adaptations such as flexible generation, energy storage or geographical aggregation in order to maintain reliable and quality  
324 energy supply [71]. Even if grid-connected renewable systems using storage exist, they still remain confined to the research  
325 field or to some prototype projects for now [72]. So, when speaking of grid-connected systems, they are tacitly regarded as  
326 systems directly connected to the grid without any kind of storage [70, 73, 74]. For the time being, the intermittency issue and  
327 this lack of storage mainly lead to limit the penetration rate of renewable energies in electrical networks, especially in low and  
328 not interconnected power grids, such as island grids [73, 75, 76].

#### 329 4.3.2. Renewable energies in off-grid electrification: stand-alone systems

330 Off-grid electrification using renewable energies is achieved with stand-alone power systems meeting the local demand of  
331 remote areas [70]. In that case, the installation almost always needs storage to suit demand and supply, and can rely on one or  
332 more renewable resources, include fossil fuel system (hybrid renewable system) and be designed as a mini-grid [70, 77, 78].  
333 Furthermore, inherent characteristics of renewable energies are also more suited to the off-grid case. First, their geographical  
334 dispersion allows some of these resources to be almost always retrieved wherever remote people are located. Second, although  
335 low capacity factor and current storage technology limit available power ranges [70, 79], it is of less concern in the case of  
336 rural electrification. Indeed, both population density, i.e. load factors, and electricity needs, particularly when the given rural  
337 area was un-electrified until then, are really low compared to urban centers [13, 43]. Lastly, the small size of the corresponding  
338 conversion systems gives them some flexibility of use, and their modularity, such as in the case of PV, allows them to grow in  
339 pace with the load [43, 70].

## 5. Resulting issues of the rural off-grid electrification using renewable energies in Sub-Saharan Africa: the example of solar PV

Depending on the *social-energy* paradigm, the use of renewable energies for providing electricity has been apprehended and promoted differently, either implemented in the original centralized electrification model or in the new off-grid pattern [13, 17, 39, 44]. The latter seems indeed the best approach for enhancing life conditions of the rural people in the least developed countries, especially in Sub-Saharan Africa where they stand for more than 60 % of the whole population . However, the success of this model shall rely on *the capacity of the couple research-industry to develop concepts and systems suited to the Sub-Saharan context*. The current issues of the few off-grid renewable applications, such as PV systems, dispatched across the sub-continent demonstrate this is not necessarily the case [15, 18, 23, 26, 27]. We propose here to expose the impact the historical need for *sustainable development*, combined with the specific power network structure of developed countries, has had on renewable systems development and sustainability in Sub-Saharan Africa by articulating our thesis around solar PV.

### 5.1. Solar PV

Photovoltaic cells encapsulated in flat modules are semi-conductors converting a part of the solar spectrum into electricity. The main component of any PV system is the PV electrical generator which is composed of several interconnected PV modules. At present time, the technology is mature and 2 main system configurations are sharing the market: the grid-connected and the stand-alone architectures.

#### 5.1.1. Grid-connected PV systems

Overall, the grid-connected model consists in a PV array connected to the electrical network through a DC/AC inverter operating in phase with the grid [73, 80, 81]. Electricity is directly injected into the power network and sold to the national electric utility through feed-in tariffs [25]. The grid-connected market is segmented between centralized, also known as *utility-scale*, and decentralized power stations [70, 82, 83]. Typically, centralized grid-connected systems are large size PV power plants directly connected to the transmission grid, while decentralized systems are medium or small size applications, such as residential or commercial rooftop PV systems, connected to the distribution network [81, 83]. Also, the coupling of these systems with storage, mainly for smoothing the production in order to prevent grid instability issues due to intermittency, mostly remains at the prototype stage [72]. The market is actually moving slowly because of the lack of markets where storage could be competitive, as a result of the cost of the storage solutions combined with the too few existing incentives [82]. Like other renewable power sources, grid-connected PV systems are therefore mainly seen and implemented without any kind of storage [73, 80, 81].

#### 5.1.2. Stand-alone PV systems

Stand-alone systems supply electricity to remote loads independently of the utility grid [70], through 3 main configurations [1, 80]:

371 **Solar water pumping:** the most simple and economical systems, only consisting of a PV array connected to a pump, poten-  
372 tially through a controller/converter. Without any storage, the production is used at once and depends on the sunlight.  
373 This kind of system is mostly used for water pumping in hottest regions [84].

374 **Classical stand-alone systems:** the most common systems, coupling PV modules with storage, such as solar home systems  
375 (SHS) [26]. This configuration allows supply of the load without interruption, the storage device being charged during  
376 the day, taking over the PV generator during the night, and acting as an energy buffer in case. In order to maximize  
377 energy flows and to protect batteries from overload and deep discharge, these systems are most of the time equipped with  
378 a charge controller; inverters are also often implemented for addressing AC needs. Regarding storage, electrochemical  
379 batteries are by far the most used at present time, in particular the low-cost and well-known lead-acid technology  
380 [85, 86]; other means such as flywheels and fuel cells are also being studied [87].

381 **Hybrid stand-alone systems:** this configuration consists in integration of other energy sources within classical stand-alone  
382 systems, in order to enhance reliability and reduce investment costs in PV modules and storage. For the time being,  
383 fuel generators are the most common secondary energy source [83], but other models of hybridization exist such as  
384 wind/solar PV [88].

### 385 5.1.3. *Solar PV: the spearhead of the renewable power systems in rural areas of Sub-Saharan Africa*

386 At the present time, modern renewable resources (hydro, solar, wind, geothermal and bioenergy) account for less than  
387 2 % of the energy mix in Sub-Saharan Africa [89]. Among these energies, solar potential is substantial throughout the sub-  
388 continent [19, 21], which explains why in rural areas, except for traditional use of solid biomass [14], solar energy is favored  
389 over other renewable resources, both in terms of existing facilities [24] and promoted energy schemes [21, 22]. Regarding  
390 off-grid rural electrification, renewable energy policies are also mainly relying on this potential [21, 23]. Globally, electricity  
391 supply using solar energy power systems is carried out through concentrating solar power (CSP) and photovoltaic technologies;  
392 the installed PV capacity is however currently 40 times larger than the CSP capacity [24]. In Sub-Saharan Africa, stand-alone  
393 PV systems, especially SHS, remain the most frequently encountered applications for providing electricity to remote areas as  
394 well as the most instigated in rural energy schemes [21–24].

## 395 5.2. *Global PV development framework: grid-connected versus off-grid systems*

396 Among modern renewable power systems, solar PV has benefited strongly from the new global energy policy during the  
397 last 20 years. The worldwide installed capacity has rapidly grown, from some hundred of MW in the middle of the nineties  
398 to 177 GW by the end of 2014, standing now for the third largest renewable power generation in the world [24]. However,  
399 this evolution hides a fundamental segmentation of the technology between both the grid-connected and off-grid architectures  
400 described beforehand.

### 401 5.2.1. *A technology market led by grid-connected systems*

402 As depicted previously in Figure 2, the growth of modern renewable energies since the eighties has more particularly  
403 quickened after the establishment of the UNFCCC and the Kyoto Protocol. The latter has directly and indirectly incited

404 industrialized countries (Annex I) to use renewable energies in order to limit their GHS emissions [10]. Since then, these  
405 resources have been taking advantage of the large amount of national renewable energy policies implemented thereafter to  
406 reach amounts of renewable power penetration into the energy schemes, corresponding to specific GHG emission reduction  
407 targets [11, 24]. As a result, the growth of the installed PV capacity has followed the same exponential curve as the global one  
408 depicted in Figure 2, and is actually one of the most significant among renewable energy systems [24, 73]. The worldwide  
409 capacity has persistently increased since the middle of the nineties, from 20%/year between 1996 and 2001 to 32%/year  
410 between 2001 and 2006 and 58%/year between 2006 and 2011 [1, 90]. The global installed power has been multiplied by  
411 more than 200 since the establishment of the Kyoto Protocol, from 0.8 GW in 1997 to 177 GW at the end of 2014 [24, 90].  
412 However, both the energy policy framework and centralized power system structure of these developed countries have led to  
413 a specific distribution of the market between grid-connected and off-grid PV systems.

414 Historically, off-grid PV systems have been leading the sector until the mid-nineties, but still within a niche market [90, 91].  
415 At the dawn of the 21st century, many incentive measures have been initiated, such as the *Renewable Energy Sources Act* in  
416 Germany [71, 92], mainly for reaching given shares of renewable-based supply in the energy mix. Regarding PV technology,  
417 it has mainly consisted in providing a public financial support so as to balance the substantial costs of the technology and  
418 initiate the market [93]. Nevertheless, these grants have primarily supplied the grid-connected systems, through attractive  
419 and guaranteed feed-in tariffs [25], while stand-alone systems have been receiving very little support [91]. This incentive  
420 policy perfectly succeeded since PV capacity has exponentially increased over the last 15 years; but this period has also stood  
421 for the success of the grid-connected over the decline of the off-grid architecture. Figure 6 depicts the evolution of the PV  
422 sector according to the system configuration in the IEA-PVPS<sup>8</sup> countries, which currently account for more than 88 % of the  
423 worldwide installed PV capacity (156 GW) against about 1 % in Middle-East and Africa [82]. This figure shows that in the  
424 early 2000, when the market was emerging, the grid-connected design began to take over the off-grid model to finally reach  
425 98.1 % of all the listed PV systems in 2011; the last available record (2014) gives the same ratio, with off-grid applications  
426 sharing between 0 and 2 % of the market [82]. In 2011, out of the 27 970 MW of PV power installed in the IEA-PVPS  
427 countries, that is 93 % of the total yearly installed power, the share of the grid-connected systems was 99.6 %.

428 As a matter of fact, both the 100 % electrification rate and centralized power system architecture have clearly driven  
429 these countries to consider the easiest way for implementing renewable energies, such as PV, in their energy mix. Two main  
430 and related reasons can explain the success of the grid-connected model. First, the need for rapidly initiating and growing  
431 the market, in order to fulfill the short-term penetration level targets established by the countries' energy policies [24, 71].  
432 Second, as a way to reduce the use of costly storage systems, the possibility, in highly interconnected power networks, of  
433 balancing the inherent intermittency of renewable resources such as PV by using geographical aggregation<sup>9</sup>, combined with  
434 the existing use of flexible generation [39, 70, 71, 73, 95].

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<sup>8</sup>International Energy Agency Photovoltaic Power Systems (IEA-PVPS) Programme

<sup>9</sup>For example, according to Jewel *et al.* [94], the PV penetration rate into the grid can rise from 1.3 % in central-station mode to a limit of 35.8 % when scattered throughout an area of 1000 km<sup>2</sup> or greater.

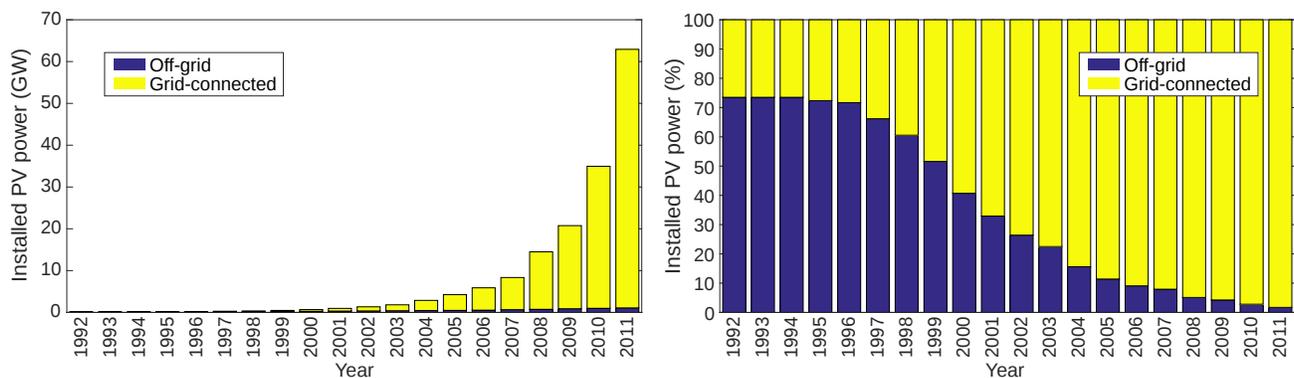


Figure 6: Evolution of the off-grid/grid-connected ratio for PV systems installed in the IEA-PVPS countries between 1992 and 2011 [91].

### 435 5.2.2. A R&D paradigm focusing on the grid-connected model

436 Upstream and alongside the industry development, the research in PV has also grown significantly within the global energy  
 437 framework. From some publications a year dealing with PV at the dawn of the fifties, this number dramatically increased after  
 438 the first oil shock, to reach around 3000 publications a year between the eighties and the end of the 20th century [96]. For the  
 439 time being, PV is the most studied technology in the field of stand-alone systems addressing rural electrification in developing  
 440 countries [13]. However, some indicators show the R&D paragon has followed the same divarication between grid-connected  
 441 and off-grid models. In fact, in the mid-nineties, Drennen *et al.* [97] considered solar PV an irrelevant economical opportunity  
 442 for developing countries, and addressed need of substantial R&D policy for including PV in the future. Since then, the  
 443 technology field has dramatically grown, but the original sector economical issues don't appear to have moved on in Sub-  
 444 Saharan Africa. In this way, many economic studies have been advising against using solar PV in the sub-continent until  
 445 today, due to the still substantial cost of the technology [23, 26, 52].

446 Although the research generally precedes the industry, the second using commercialized version of the concepts and pro-  
 447 totypes the first has developed, the path followed by the latter, mainly resulting from the policy framework, might also drive  
 448 the R&D paradigm. In [1], we have analyzed the main topics of the European Photovoltaic Solar Energy Conference (EU-  
 449 PVSEC), which is regarded as “the largest international conference in the field of Photovoltaics” as well as a “world renowned  
 450 science-to-industry platform” [98]. Storage coupled to an intermittent source is the essential element which differentiates the  
 451 stand-alone from the grid-connected configuration. The second criterion is about the conditions the systems will be operating  
 452 in, affecting both efficiency and reliability, such as climate, operating environment or availability of human monitoring; all or  
 453 part of these conditions are different in Sub-Saharan Africa in comparison with developed countries where most of the systems  
 454 are established. Analysis of the EUPVSEC emphasizes the means the research allocates to these criteria. In 2012, they ac-  
 455 counted for approximately 8 % of all the oral communications [1, 99], half of them being focused on PV module degradation,  
 456 the other half being dedicated to the storage (2 %) and to the global stand-alone system itself (2 %). If it confirms the shape of  
 457 the PV market, it is also relevant to note that the meeting of the technology (modules + storage + electronics) with the context  
 458 specific conditions (Sub-Saharan arid/tropical climates, less developed countries) appears to be a void in the research field.

459 This pattern is also corroborated by authors having addressed either the still significant amount of research needs for meeting  
460 the off-grid system specific challenges in developing countries [15], or the scarce existing literature about synergizing all PV  
461 facets into comprehensive off-grid application studies [27].

### 462 5.3. *Impact on off-grid PV sustainability in Sub-Saharan Africa*

463 The global energy policy over the past 40 years, coupled with the specific power supply architecture of developed countries,  
464 has led to a specific compartmentalization of the PV sector, in both industry and research, as a result that the grid-connected  
465 development is now by far prevailing over the off-grid one. Lack of knowledge about the challenges of operating stand-  
466 alone systems in a different context such as Sub-Saharan Africa has inevitably arisen in the wake of this pattern, resulting in  
467 sustainability issues for the off-grid applications effectively set up on site and uncertainty about the future of these systems.

#### 468 5.3.1. *Lack of feedback and expertise*

469 The most obvious consequence of the historical development of the PV market around the grid-connected pillar has been  
470 the inevitable lack of feedback and expertise for stand-alone PV applications, especially in the specific context of developing  
471 countries [15, 18]. In fact, if the global part of the off-grid market is evaluated around 2% [90], 85% of all the corresponding  
472 systems are currently located in the IEA-PVPS countries [91]. In Africa, even if PV is promoted over other renewable  
473 resources, the sector is still in its infancy [25]: despite the lack of available data, the installed PV capacity, mainly consisting  
474 of small stand-alone applications, such as SHS and SPS [24, 25], was estimated under 200 MW in 2010 [100, 101]. This  
475 capacity was around 600 MW by the end of 2013 and is increasing since then, but almost exclusively in the 2 biggest markets,  
476 that is South Africa and Algeria, and mainly supported by policies promoting utility-scale PV projects [24, 25, 102, 103].

477 Regarding the current operating systems, different studies have pointed out the low monitoring of rural off-grid PV projects  
478 and programs in developing countries [15, 18]. This absence of systematic evaluation of population field experience with  
479 decentralized PV systems has led to a significant void in documentary information [15, 18]. It echoes the observation made  
480 by Chaurey *et al.* on the corresponding research field [27]: if the literature has proposed approaches for wider dissemination  
481 of off-grid PV systems, it has meanwhile poorly depicted the challenges related to marketing, dissemination and use of these  
482 systems.

483 The national or international level of expertise in a specific energy sector can be apprehended from its technological  
484 progress status, that is from the properly operating field applications which have been developed. For instance, Iceland is  
485 currently the world leader in geothermal installed power and production per capita [24], and its authority on this technology is  
486 such that other countries, like Kenya or Djibouti, draw on its expertise [104, 105]. At the present time, in the rural framework,  
487 in spite of being preeminent in field projects and renewable energy policies of Sub-Saharan Africa, the PV technology remains  
488 globally confined and locally mostly present in developed countries. Also, the existing decentralized facilities seem to run  
489 anonymously, with almost no technical monitoring which would allow fast and easy feedback for enhancing system R&D.  
490 This pattern coherently meets the limited investigation made by industry and research in the field of stand-alone systems,  
491 especially in the context of Sub-Saharan countries.

492 5.3.2. *Critical social-technological issues affecting sustainability of off-grid PV systems in the Sub-Saharan context*

493 At the present time, the situation we have been depicting until now is as follows: the global energy policy framework has  
494 impacted the industrial and R&D PV sectors, leading to a tremendous underdevelopment of the PV off-grid market, especially  
495 in the Sub-Saharan context, in which there is also no transfer of experience and knowledge from the few systems operating in  
496 the field.

497 Sustainability issues, and related challenges, of off-grid PV systems in Sub-Saharan Africa mainly arise at the interface  
498 of both social and technical paradigms [15]. Technical issues, deriving from the lack of industry development and system  
499 R&D, combined with the lack of science interdisciplinary cooperation have been leading to a failure in developing the right  
500 strategies for implementing these systems in Sub-Saharan remote locations [15, 27].

501 *Off-grid PV behavior in the Sub-Saharan environment*

502 In order to apprehend the main potential technical issues of stand-alone PV systems in Sub-Saharan Africa, we must  
503 describe the influence of exogenous parameters (operating environment) on the behavior of a PV system (efficiency, reliability,  
504 degradation). Though system interaction with wildlife, such as cables affected by mice and rats [15], may also be accounted  
505 into operating environment, we mainly focus here on climatic conditions altering the sub-system's endogenous features. In  
506 fact, most of the climates throughout the sub-continent are either equatorial, tropical or arid [106]; analysis of the behavior of  
507 off-grid PV systems operating in conditions characterized by high temperature, high humidity or else a significant amount of  
508 dust is therefore of prime importance.

509 Regardless of the material properties and the installation type, operating cell temperature mainly increases with incident  
510 radiation and air temperature [107], and can significantly cut down the available power, i.e. mitigate efficiency, of a PV  
511 module [88, 108]. Leaving aside the incident radiation, the PV module yield can also be mitigated by the increase of ambient  
512 air temperature alone [109, 110]. In the same way, rise of the temperature, as well as the moisture, may strongly reduce  
513 reliability and lifetime, i.e. increase the degradation rate, of both PV fields and electric converters (charge controller, inverter)  
514 [15, 111–113]. For the very widespread mono-crystalline and polycrystalline PV modules, the degradation rate rises for  
515 instance from a nominal value about 0.5%/year [114, 115] to 1%/year in arid climates [114, 116], and appears even more  
516 substantial in Sub-Saharan environmental conditions, up to 3% [117]. In relation to converters, as charge regime is a critical  
517 point for maintaining battery service life [86], malfunctioning charge controllers have also been found to be often responsible  
518 for failure and lifetime mitigation of batteries [18].

519 Dust's major contribution is related to the PV module efficiency decrease due to soiling [118–120], which has led several  
520 authors to address requirements for PV module cleaning, in particular integrated into plans of periodic preventive maintenance  
521 [118, 119]. Dust's minor contribution concerns its impact on PV panel degradation over lifetime, which has been for example  
522 estimated around 16-29% of the global power losses by Tanesab *et al.* [121].

523 Like the other components of the system, performances of the electrochemical storage also strongly depends on these  
524 criteria. With reference to aging, battery nominal lifetime is thus halved for each increase of 10°C above the reference  
525 operating temperature [122, 123], and rainy seasons of equatorial and tropical countries are also a source of damage, and

526 then of lifetime mitigation [15]. Especially, in addition to this statement, the very used lead-acid batteries already present  
527 short nominal lifetimes combined with intolerance to extreme temperatures [124]. This is a cause for concern as it makes the  
528 batteries still standing for the major contribution to the life-cycle investment of a stand-alone PV system [12, 18, 66]; their  
529 multiple replacement along the overall system lifetime reduces its economic relevance.

#### 530 *Socioeconomic implications of the stand-alone PV system R&D requirements in Sub-Saharan Africa*

531 The main socioeconomic implications spring out from the light thrown on the stand-alone PV system reliability, degra-  
532 dation and performance issues within the specific Sub-Saharan rural context, deriving from the impact of the operating en-  
533 vironment on the material endogenous features. The extreme remoteness of the populations makes these technical issues  
534 especially critical as maintaining performances and reliability requires in particular monitoring systems, performing repair  
535 and maintenance or else providing spare parts [15, 18, 27]. The corresponding challenges reflect the lack of PV transdis-  
536 ciplinary R&D [15]. Regarding system promotion, installation and maintenance, lack of skilled technicians or knowledge  
537 transfer between PV producers and fitters/users is pointed out; system failures thereby often result from unsuitable design,  
538 improper installation, use of unreliable components or poor maintenance [15, 27, 125, 126]. Besides, users are also often  
539 left on their own with their system after the initial installation, without any real after-sales service structure or proper training  
540 [52]. Technology-user interaction is therefore addressed as a critical point in the literature [15, 27, 125, 126]: maintaining  
541 system proper performances and reliability in remote areas requires user operation training and significant understanding of  
542 the very specific characteristics of the system, but still appears to be left out. Daily deteriorated system performances resulting  
543 from operating environment, especially owing to the batteries [127], are another cause for concern. Disappointment may for  
544 example arise from the differential between user expectations and the system energy performance ultimately delivered on site,  
545 as the installation cannot always supply the intended user needs because of the incomplete or wrong information about its  
546 real-conditions operating capacities [15, 27].

547 Another consequence is the very high cost of off-grid PV systems in Sub-Saharan Africa, which affects related financing  
548 schemes used for system dissemination, mainly due to operating and maintenance charges required for counterbalancing the  
549 aforementioned reliability and performance issues [26, 27, 52]. Potential users are often unaware of these extra costs in  
550 addition to the PV system initial investment, as they are generally underestimated in financial schemes, and have therefore  
551 to cope with it while they are repaying the credit [52]. For instance, specific electrochemical storage short-term issues can  
552 lead stand-alone systems to operate with poor batteries [128], or for the users to be forced to give up on their installation after  
553 battery failure and revert to their previous energy supply while still paying system investment credits [15]. As a result, the  
554 first targeted households for using these systems are also the ones that can hardly afford the cost of such facilities [52], which  
555 therefore require innovative financing schemes such as fee-for-service or donation delivery mechanism [18, 27, 129]. However,  
556 when off-grid PV projects rely on the latter, they generally fail because of lack of user commitment, as they are less involved  
557 and feel less responsible than for a purchased system [18]: maintenance for sustainable operation is not originally understood,  
558 savings for battery replacement are not necessarily made, and use of the system is therefore more easily abandoned.

## 6. Conclusion and prospects

The *sustainable development* concept sprung up in the developed countries, in the wake of the questioning, which emerged in the seventies, on the impact of their historical development on the living environment [5, 8]. It has been shaping the global policy framework since the nineties, starting with establishment and ratification of both UNFCCC and Kyoto Protocol by most of the countries in the world [9, 10]. This global framework has been then implemented locally in national climate change policies, from developed to developing countries, including Sub-Saharan Africa [21, 22, 130, 131]. In this way, GHG emission reduction targets of the Kyoto Protocol have directly and indirectly supported the use of renewable power sources, resulting in many local policies having sparked the tremendous growth of these resources, especially the modern sector such as wind or solar PV [11, 24, 40]. However, the power system centralized architecture of the most developed regions in the world, directly stated by the Kyoto Protocol disposals for reducing their GHG emissions, has led to a significant divarication of the renewable power supply global market between grid-connected and off-grid sectors. This is particularly manifest for solar PV systems, which have moved on from a narrow market dominated by off-grid facilities in the mid-nineties to the third renewable power installed capacity in the world in 2014, mostly in developed countries, with the grid-connected design sharing for more than 98 % of all installations [24, 91]. In short, the need of developed countries for reaching short-term GHG emission reduction targets, according to *sustainable development* requirements, has driven industry and R&D to focus on the grid-connected architecture. This model allows replacement of traditional fossil fuel plants by renewable power systems in highly interconnected electrical grids, taking advantage of geographical aggregation and existing flexible generation instead of costly storage systems in order to limit intermittency issues [39, 70, 71, 73, 95]. On the other hand, the need of Sub-Saharan Africa for increasing rural access to electricity, in order to enhance *human development* of most of the population, has led to the consideration of off-grid electrification [1, 13, 43, 53, 68, 69].

This global framework has shaped the current status of off-grid renewable power systems in Sub-Saharan Africa. Regarding solar PV, although it remains the most encountered technology in the field and the most instigated in both R&D and energy incentive policies [13, 21, 22, 24], the installed capacity is still very low and the last improvements have mainly affected utility-scale facilities [24, 25, 102, 103]. Feedback about how these few systems are in fact operating in the specific Sub-Saharan field has been definitely lacking, and research has meanwhile been following the industrial path by leaving aside the off-grid system specificities. As a result, R&D original challenges and needs, arising at the interface of both technological and socioeconomic issues in the Sub-Saharan context, appear to have been left untouched [15, 18, 27].

About 95 % of the renewable energy policies have followed the UNFCCC and 90 % the Kyoto Protocol [11]; it makes therefore really questionable the original goal behind the implementation of these resources in Sub-Saharan countries' energy schemes. In the region, it seems indeed it has never been really clear whether renewable energies were an artifact from and for sustainable development and climate change policies or an electrification mean to address poverty mitigation [21, 22, 52, 64, 130, 131]. This somehow *schizophrenia* is especially apparent when confronting the aforementioned promotion and use of solar PV for electrifying remote areas of the sub-continent with the literature having meanwhile considered it economically unfeasible over the last 20 years [23, 26, 52, 97, 126]. The paradox arising from this situation is two-fold, so that neither

593 sustainable development nor human development requirements have been really fulfilled in Sub-Saharan Africa. As a matter  
594 of fact, in the region, so-called *sustainable* off-grid energy power systems remain scarce and subject to sustainability failures<sup>10</sup>,  
595 while multidimensional poverty is still as significant as the electrification rate is low [14, 46].

596 As an opening to this global overview, we might ask: is human development more rightful than sustainable development  
597 in Sub-Saharan Africa, or is it possible to make both, and their corresponding requirements, more compatibles ?

598 The first part of this question requires us to put the global sustainability issue into perspective. Between 1850 and 2005,  
599 the most developed countries (HDI > 0.8) have been responsible for almost 64 % of all CO<sub>2</sub> emissions [1, 3]. For now, the gap  
600 in GHG emissions, primary energy supply or electricity consumption between Sub-Saharan Africa and developed countries  
601 is still tremendous; as an example, IEA countries, having originally supported the current global energy framework, stand for  
602 amounts respectively 7, 14 and 21 times larger than Sub-Saharan countries [1]. Not only the historical responsibility in both  
603 global warming and resources depletion issues but also the current situation are therefore completely unbalanced between Sub-  
604 Saharan and developed regions. Actually, the significant human development of the most industrialized regions in the world  
605 has given them the latitude to rethink their development path, whose historical global consequences seem to have restrained  
606 the latitude of the developing regions to achieve their own.

607 From this pattern, it is probably legitimate to consider both the paragons having to get along with each other, using  
608 their own *fitted means* to limit, for developed regions, negatively affecting their environment (sustainable development) and  
609 increase, for Sub-Saharan Africa, the population's standard of living (human development). Nevertheless, as a first step in an-  
610 swering the second part of the original question, we may remind ourselves what we depicted in section 3.4.3: GHG emissions  
611 and primary energy supply are mainly related to economic growth, while enhancing education and health criteria of human  
612 development is of lower influence. In the first stages of diminishing multidimensional poverty, by removing deprivations  
613 in every dimension accordingly, electrification would therefore be a *qualitative* energy supply vector whose environmental  
614 impact would remain circumscribed. This could be then the first step towards aware populations, equipped with the right  
615 instruments for promoting a different path, a *sustainable* path, to the next stage of their development.

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<sup>10</sup>Note that this is actually also somehow true for most of the grid-connected systems at the moment, as power networks and infrastructures remain particularly unreliable in Sub-Saharan Africa, and therefore technically unsuited for merging substantial intermittent renewable power [64, 65].

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