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State of play of the global energy context and the deployment of hybrid systems in autonomous grids

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Abstract

The increase in global energy demand is closely in correlation with economic activity. Energy intensity has resulted in the increase in the consumption of fossil fuels, which have mainly imposed themselves in the energy mix.

The energy transition contributes to the security of supply and the reduction of energy dependence, particularly in vulnerable areas with difficulty in connecting energy where electricity is required to meet local demand. To connect isolated populations, autonomous grids running on renewable energies are crucial. The renewable potentials of these regions can meet load demand by reducing fuel consumption and energy dependence by making electricity networks profitable.

Hybrid renewable energy systems make it possible to combine several electricity production resources, conventional and renewable for better performance.

Keywords: Autonomous grids, Energy, Electricity, Hybridization, Renewable energy.
JEL Codes : Q42 ; Q48 ; R34

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1. Introduction

It is an undeniable fact that energy is a key component of global economic development (Simcock, 2020, p. 1). To produce energy, most countries rely heavily on fossil fuels, which are fuel-based products. According to (Graus & al, 2011) , these energy sources accounted for 80% of the world's primary energy supply in 2005 and are expected to have the same share by 2030. In 2021, global energy demand increased by 5.4%, this increase is partly due to the increased use of coal which resulted in an increase in emissions of 1.9 gigatons (Gt) in 2021 (IEA, 2022, p. 124). However, fossil fuels are non-renewable, diminishing, depleting, and not maintained. The world's population and the economic growth of countries are increasing such that the demand for energy is greater than the energy produced from conventional resources. According to BP's 2023 report (BP, 2023), global energy demand will continue to grow by an average of 1.5% per year through 2035.

The world demand for energy has increased by about 93% in the last thirty years, reflecting the intensity of global economic activity, especially in emerging countries that have experienced strong economic growth. The consumption of fossil fuels, namely coal, oil and natural gas, is constantly increasing and now accounts for more than 80% of the world's primary energy consumption.

Energy independence is one of the main priorities of governments and implies the urgent need to develop renewable energies in the future. Indeed, these perennial sources derived directly from natural phenomena reduce dependence on external fossil fuel markets and provide clean alternatives to conventional energy (Roth & al, 2017, p. 160).

The deployment of renewable energy in electricity generation has attracted great interest in recent decades. As much as an indicator of the economic and social development of countries, the growth of this sector is driven by the renewable energy sector; namely, solar photovoltaic, hydroelectricity and wind power, while the consumption of renewable energy is increasing every year by 3%. It is in this sense that the development of energy access compiled with the commitment of countries in their energy transition has promoted the adoption of concrete solutions to build a sustainable energy future independent of fossil sources (Energy Academy, 2020) (Bustos & Watts, 2017, p. 206). Autonomous grids are a reliable solution for vulnerable areas to ensure their integration into energy mixes and ensure the sustainability and profitability of electricity grids (Vanadeina & al, 2019) (Ayodele B. E & al, 2019) (López-Gonzáleza & al, 2019).

2. The world energy situation

The modern world energy situation, based on the growth of the economic dynamism of countries, has resulted in a continuous increase in energy demand. Energy consumption is, strongly dominated by fossil fuels, which represent more than 80% of primary energy sources (BP, 2022). Dependence on fossil fuels leads to vulnerability, according to the IEA, energy production is expected to double over the next fifty years to meet the needs of dynamically growing countries whose drivers are led by developing economies (IEA, 2017), including China, India, Brazil and others.

2.1. The global energy situation

It is generally accepted that economic growth means more energy consumption. Although this should be rational, primary energy demand increased by 27.9% between 1980 and 2000 and by 39.7% between 2000 and 2020 as presented in Table 1. The increase in primary energy demand is driven mainly by natural gas. This implies a growing dependence on gas supplies. On the other hand, the global energy mix is largely dependent on oil, whose consumption has grown at an annual rate of 1.3% since 2008. Oil consumption has increased from 84 million barrels per day in 2009 to just over 98 million barrels per day in 2019 (BP, 2022). Global demand for primary energy has increased from 7 billion tons of oil equivalent (toe) in 1970 to 14 billion tons of oil equivalent in 2017, a change of over 93%.

Table 1: Evolution of primary energy demand by region (Mtoe)

	1980	1990	2000	2010	2018	2019	2020
North America	2 092	2 260	2 670	2 677	2 714	2 765	2 571
USA	1 802	1 915	2 270	2 214	2 230	2 236	2 108
Brasilia	114	138	185	262	285	318	312
Europe	1 493	1 630	1 734	1 837	2 000	1 907	1 850
European Union	n.a	1 633	1 682	1 713	1 613	1 402	1 325
Africa	274	388	502	690	838	826	811
Japon	345	439	519	497	434	415	386
Russia	n.a	880	620	710	751	768	740
Asia	1 067	1 589	2 172	3 936	5 985	6 242	6 194
China	603	881	1 107	2 416	3 187	3 314	3 488
India	208	317	459	691	916	929	888
Middle East	128	210	381	624	763	785	768
Latin America	292	331	456	586	660	680	642
World	7 229	8 779	10 031	12 730	13 760	14 638	14 016

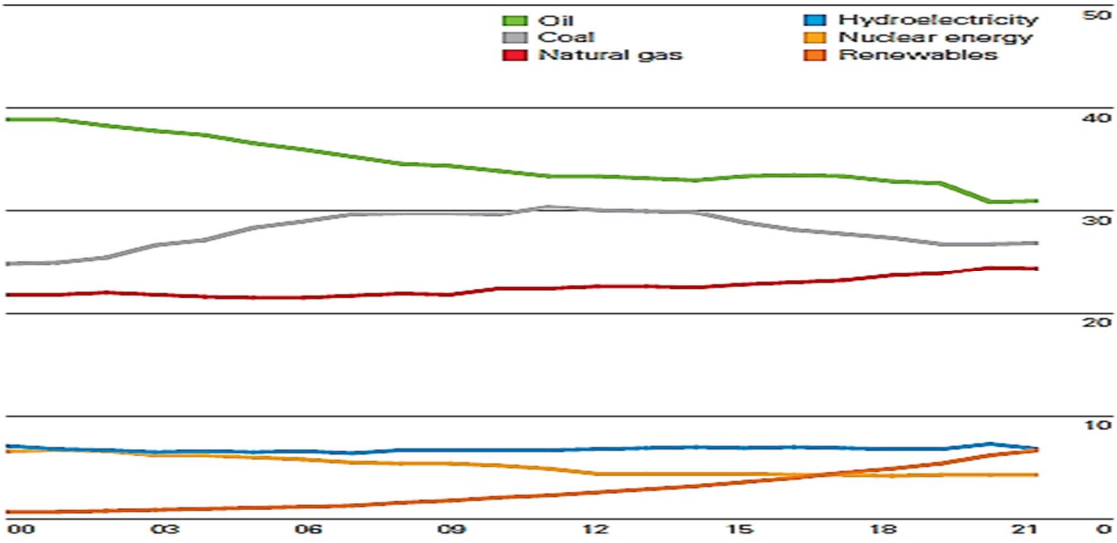
Source: based on the World Energy Outlook (IEA).

Most of the global increase in primary energy demand is coming from non-OECD countries due to rapid economic growth in emerging economies and continued subsidies on petroleum products in Middle Eastern countries. Before the 2000s, North

America and Europe accounted for more than 43% of global energy demand and developing economies in Asia for about 20%. Since then, the very rapid pace of energy demand growth in these countries reflects accelerated growth rates in economic activity, particularly China, which alone accounts for 22.26% of global demand in 2018 and about 25% in 2020. This situation represents a huge shift in the geography of energy consumption where China consolidates its position as the largest energy consumer, followed by the United States with 15% and India with 6.3% of global primary energy consumption.

Fig.1 shows that in 2021, global energy consumption slowed by 1.3% compared to previous years. It grew at a rapid rate of 2.9% in 2018, 2.2% in 2017, 1.8% in 2012, and 2.7% in 2005. Natural gas contributing more than 40% of the increase of the global energy consumption (BP, 2022, p. 31). As a result, fossil fuels continue to provide the bulk of global energy consumption.

Fig.1: Shares of global primary energy consumption by source (%)



Source: (BP, 2022, p. 10)

Oil is the most used energy in the energy mix, followed by coal and natural gas with 31% and 24.4% in 2021. Towards the end of the 1990s, oil's share of primary energy consumption has been steadily slowing down and the growth in demand of natural gas has increased by 43% in 10 years (BP, 2022, p. 52). In 2021, oil consumption is concentrated in Asia-Pacific and North America, representing 64.48% of world consumption. Asia-Pacific region consume heavily coal, while more than two thirds of nuclear consumption is concentrated in North America and Europe. Asia-Pacific accounts for more than 43.3% of hydropower. The promotion of energy efficiency has had a significant impact on moderating energy demand growth. As a result, Asia-Pacific consume just under 90% of renewable energy, Europe and North America. In 2021, the contribution of hydroelectricity will represent 7% of the world energy mix. Paraguay is one of the largest hydroelectricity producing countries in the

world, drawing its energy from the hydroelectric plant built in 1973 with Brazil and Argentina in Itaipu on the Panama River. Itaipu has an installed capacity of 14,000MW and an annual production of 98,289 GWh (Blanco & al, 2017). The plant provides 17% and 75% of the respective energy consumed in Brazil and Paraguay. Hydropower accounts for approximately 99.99% of the electricity generated in Paraguay (Lorenzon & al, 2016).

2.2. The world's proven fossil fuel reserves

Fossil fuels are unevenly distributed. The world's proven reserves are the amounts of oil, natural gas or coal that can be recovered in the future from deposits under known and existing economic and operating conditions (Table 2).

Geological and technical information indicates that the Middle East has the largest share of proven oil and natural gas reserves. As for coal, Asia-Pacific holds more than 40% followed by North America and the Commonwealth of Independent States.

Table 2: World's Proven Fossil Energy Reserves

	Oil (10^9 baril)	Natural Gaz (10^{12} m^3)	Coal (10^6 tonnes)
End 1999	1277,1	132,8	1 058 811
Ratio R/P	48,34	56,46	227,5
End 2009	1531,8	170,5	928 238
Ratio R/P	45,7	62,8	119
End 2019	1733,9	198,8	1 609 636
Ratio R/P	49,9	49,8	132

Source: based on BP reports

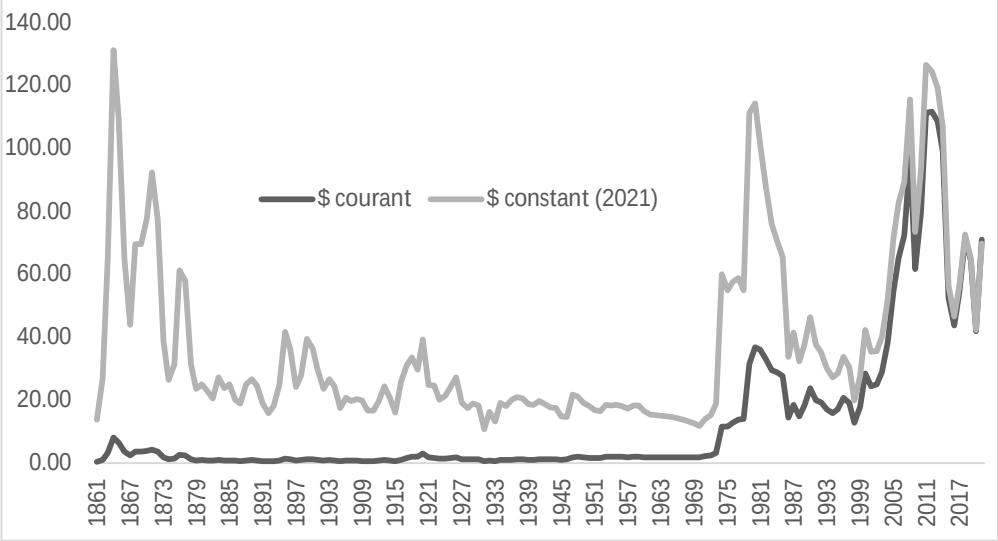
The world has proven oil reserves stood at 1,734 billion barrels at the end of 2020, an increase of 456.8 billion barrels in 20 years. The countries of the Organization of the Petroleum Exporting Countries (OPEC) own more than 70% of the world's oil reserves. The R/P ratio shows that oil reserves in 2020 represent 50 years of current production, two years more than in 1999. South and Central America has the highest ratio, 144 years, while Europe has the lowest (12 years).

The world's proven natural gas reserves have increased by 66 trillion cubic meters from 1999 to 2019, or about 50%. Russia, Iran and Qatar are the countries with the largest reserves with 38, 32 and 24.7 trillion cubic meters respectively. The R/P ratio shows that gas reserves in 2019 represented 49.8 years of current production. The Middle East and CIS are the regions with the highest R/P ratio.

Global coal reserves are over 1.6 trillion tons at the end of 2019, up 681 billion tons from 10 years ago. Concentrated mainly in a few countries, notably, the United States with 23%, Russia 15%, Australia 14% and China 13%. A little more than 70% of the reserves are anthracite and bituminous. The R/P ratio shows that current coal reserves represent 132 years of current production.

Oil is the most consumed energy source in the world. In 2021, 94,088 thousand barrels of oil are consumed every day (BP, 2022, p. 20). Considered as the indispensable ingredient for the proper functioning of the world economy, the volatility of oil prices has a direct link to the geopolitical situation, political crises of countries, OPEC decisions, etc. The price of a barrel of Brent crude oil rose from 3.29 dollars at the beginning of 1973 to 96.26 dollars in 2008 and thus multiplied by 29. The oil peak is reached between 2011 and 2014 (Fig.2).

Fig.2: Evolution of Brent oil prices, 1861-2021



Source: based on BP database

The 1973 oil shock led to the abrupt change in oil prices (Mouhoubi, 2012, pp. 162-163). The price of a barrel rose from $1.05 in late 1945 to $11.58 in 1974. The years after 2000 are marked by the increased growth of the price per barrel due to the structure and economic conditions of the oil market following the increase in demand from emerging countries such as India and China and the global economic recovery.

Between 2014 and 2015, prices fell from 98.95 to 52.39 or 47%, following the decision of OPEC to maintain the level of supply unchanged in addition to an economic slowdown of some emerging countries including China and the rise in production of unconventional oil by the United States followed by Russia and Qatar. This continuous price collapse has led to a reduction in the quantities of oil imported by OECD countries as well as a decline in the revenues, budgets and external balances of exporting countries. The year 2020 is marked by the spread of the COVID-19 pandemic, which has impacted energy markets, with primary energy falling at its fastest rate since the Second World War. Primary energy consumption fell by 4.5% in 2020, the largest drop since 1945. This is mainly due to the decline in oil, which has contributed to nearly three quarters of the net decline where prices have fallen to $42/b to recover in 2021 to an average of $70.91/b, the second highest level since 2015.

2.3. The future energy outlook

No one can predict the evolution of prices, the expected level of demand or the world's energy future. Prospective exercises conducted by the major players on the international energy scene seek to use the latest energy data to provide medium- and long-term forecasts by building scenarios and exploring possible futures. They often consist of moving from the current energy system to an energy mix that relies mainly on renewable energies or even on renewable energy sources for human activities.

Three scenarios are based by the IEA and provide frameworks for thinking about the future of global energy. According to them, the energy outlook to 2040 indicates a prolonged dominance of oil, gas and coal (Table 3). The estimated developments in the global energy system stipulate that the deployment of new renewable capacity is a proven means to achieve multiple energy policy objectives, namely the promotion of energy efficiency.

Table 3: World Primary Energy Demand Scenarios by Fuel (Mtoe)

			New politicies		Current policies		sustainable developpement	
	2000	**2017**	**2025**	**2040**	**2025**	**2040**	**2025**	**2040**
Oil	3 665	4 435	4 754	4 894	4 902	5 570	4 334	3 156
Coal	2 308	3 750	3 768	3 809	3 998	4 769	3 045	1 597
Natural gas	2 071	3 107	3 539	4 436	3 616	4 804	3 454	3 433
Nuclear energy	675	688	805	971	803	951	861	1 293
Renewables	662	1 334	1 855	3 014	1 798	2 642	2 056	4 159
Solid Biomass	646	658	666	591	666	591	396	77
Total	10 027	13 972	15 388	17 715	15 782	19 328	14 146	13 715
Part of fossil fuels	80%	81%	78%	74%	79%	78%	77%	60%
CO_2 Emissions (Gt)	23.1	32.6	33.9	35.9	35.5	42.5	29.5	17.6

Source: WEO, 2018

In the New Policies Scenario, global primary energy demand increases by just over a quarter between 2017 and 2040. Natural gas is expected to experience the strongest growth and nuclear power is expected to maintain a gradual recovery. As for other energies, they are developing very slowly.

India's energy demand will more than double by 2040, becoming the main source of global growth. China's energy consumption is also rising sharply, but the growth rate is only one-fifth of that observed between 2000 and 2017.

Under current policies, global primary energy demand grows by nearly 40% between 2017 and 2040. By then, 78% of generated energy comes from fossil fuels. Coal use increases due to high consumption in developing countries, notably the Middle East, India and China. This current policy scenario tends to ensure a continued decline in energy consumption in the European Union and Japan in 2040 and China becomes the world's largest oil consumer. In the absence of significant additional

commitments, renewable energy develops slowly and is limited to 13.6% of the total in 2040.

In the sustainable development scenario, coal demand is only 1,600 million tons of oil equivalent (Mtoe) in 2040, less than 66% of the current policy scenario. Oil demand peaks and begins to decline. Natural gas consumption increases in all scenarios, supported by its environmental advantages over other fuels, despite its limited growth prospects in this scenario.

3. Overview of renewable energy in the world

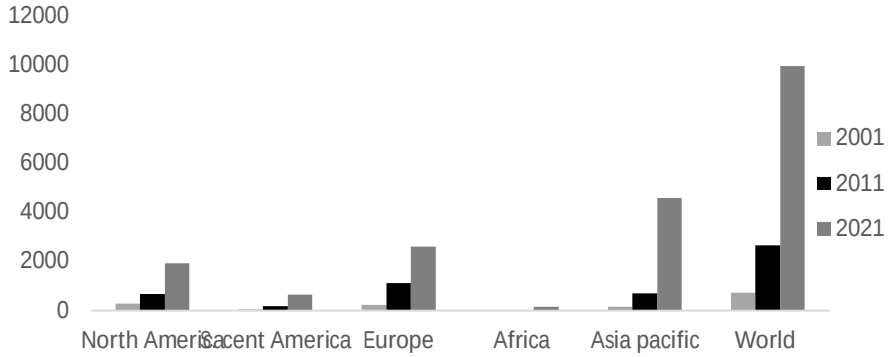
Renewable energies are energy sources that are continuously replenished by nature and derived directly from the sun (such as thermal, photochemical, and photoelectric), indirectly from the sun (such as wind, hydroelectricity, and photosynthetic energy stored in biomass), or from other natural movements and mechanisms in the environment such as geothermal energy (Ellabban & al, 2014). Renewable energies have become an important component of the energy mix in recent decades. Indeed, they reduce the use of conventional energy systems based on resources of fossil origin and consequently, the environmental and socio-economic pressures of their use.

The energy transition challenges the energy-intensive development model that contributes to the depletion of fossil resources in the medium and long term. The promotion of Renewable energy development strategies are with the primary objective of offering societies an energy service at an acceptable price.

3.1. The use of renewable energy

Fig.3 presents global renewable energy production by region; it has increased by 3,242.5 TWh between 2001 and 2021. The main reasons for the increase in renewables relate to political support and financial commitments associated with some governments such as feed-in tariffs, power purchase agreements and reduced production costs.

Fig.3: Evolution of global RE production by region (TWh)

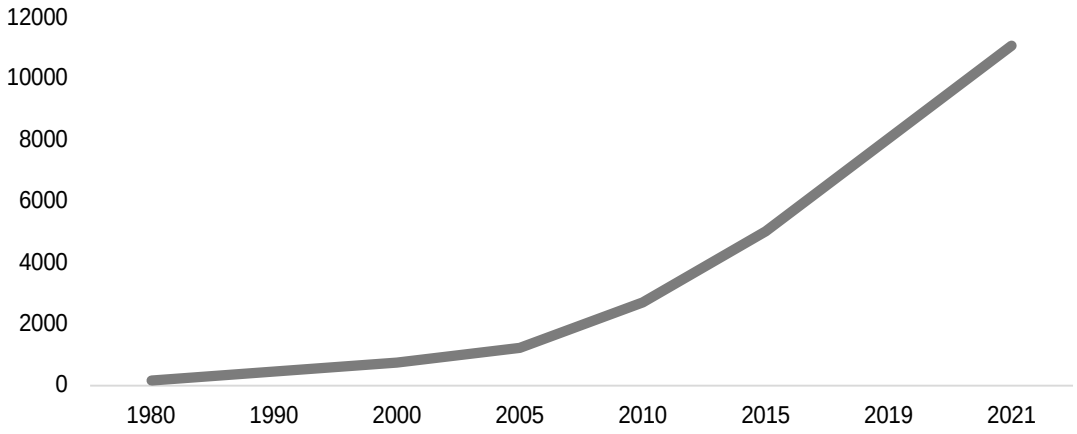


Source: based on BP database

Global renewable energy production increased by 16% in 2021. The annual growth rate is 14.2% between 2011 and 2021. The increase in renewable energy production is due to the exploitation of renewable deposits where the world's hydroelectric potential has increased by nearly 60% in twenty years taking advantage of huge developments, especially in Asia Pacific countries, with a contribution to global production of 21% in 2001, 25.73% in 2011 and 46.1% in 2021. China's renewable energy production has increased six fold, making it the world's leading producer of renewable energy with 30.5% in 2021. African countries will only contribute 8.1% of the world production in 2021 and remain dependent despite the implementation of energy policies for the promotion of renewable energy and the realization of major projects for the production of renewable electricity in some countries such as Morocco and Egypt.

However, a little less than 7% of the world's primary energy consumption will come from renewable energy sources in 2021. However, the consumption of renewable energy sources has increased more than proportionally since the 2000s as shown in Fig.4 where it has increased by a factor of 9.13 between 2005 and 2021.

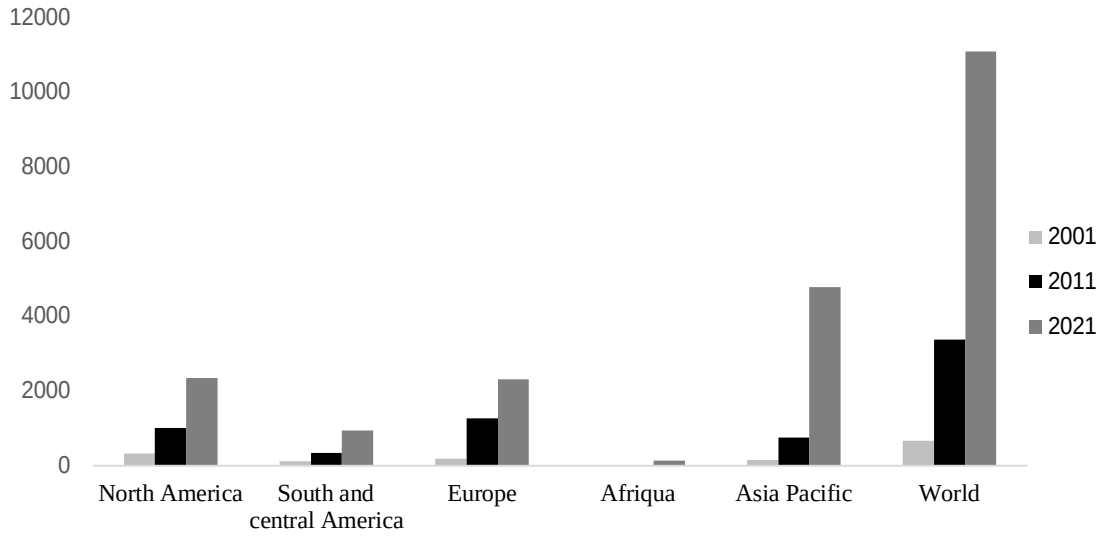
Fig.4: Evolution of renewable energy consumption in the world (TWh)



Source: based on BP database

According to the Fig.5, over the past two decades, the great interest in renewable energy in the energy and electricity mix of the countries has resulted in a consumption that has increased 15-fold between 2001 and 2021. In 2019, the latter is estimated to be 13.3% higher than 2018. The share of renewable energy consumption also increased from 13.33% to 18.86% between these two periods (Wang & Wang, 2020). The annual growth rate of global renewable energy consumption was 15.5% between 2008 and 2018 and 20.5% between 2011 and 2021.

Fig.5: Renewable energy consumption by region (TWh)



Source: based on BP database

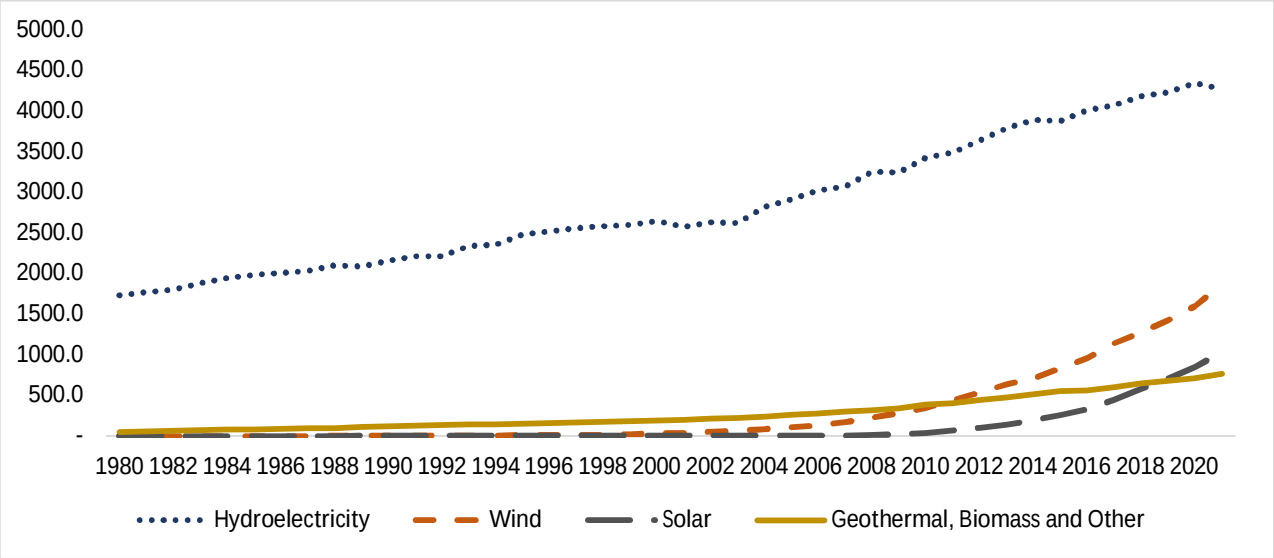
The annual growth rate of renewable energy consumption is 10.9% between 2008 and 2018 and 12.6% between 2011 and 2021, a rate that was only 3.2% over the period 2000-2018. The share of renewable energy in the global energy mix has increased significantly from 3.1% in 1990 to 13.3% in 2019. These figures are explained by the increasing share of solar (40.1%), wind (19.9%), liquid biofuels (16.7%), biogas (8%) and solar thermal (5.6%), respectively (Hemachandra & al, 2020). In addition, OECD countries have been using renewable energy in the transportation sector (IEA, 2020) to protect environmental quality for the past three decades. Given concerns about carbon emissions and climate change, these countries are increasingly focusing on diversifying the energy mix and securing energy supply.

The Asia Pacific region has marked the last decade with very high growth rates, amounting to 20.5%. In 2021, China is the leading contributor to the growth of renewable energy consumption with a growth rate of 33.1% compared to 2020; its consumption has increased 20-fold over the past 10 years (BP, 2022, p. 50). Chinese consumption accounts for 28.4% of global consumption, followed by the United States, Germany and India with 18.7%, 5.7% and 4.5%.

The share of renewable energy consumption in Africa is set at 1.2% of global consumption in 2021. This is due to the low energy yields of these sources, the accumulated delays in the sectors and the high technological and scientific levels required.

The penetration of renewable energy sources contributes to reducing energy dependency while promoting investment and job creation. Fig.6 shows that global production of renewable energy sources has increased on a large scale in the hydro, wind, and solar renewable energy sectors.

Fig.6: Global renewable energy production by source 1980-2021 (TWh).



Source: based on BP database

According to the above data and the Figure, hydropower is the most produced renewable energy in the world. Global hydropower generation grew by about 18.27% between 2011 and 2021 and by 39.63% since 2011. The annual growth rate between 2011 and 2021 is at 2%. The hydroelectricity generated remains highly variable from one year to another and from one country to another depending on the climatic conditions of the countries and the hydraulic potential. It plays an essential role in the production of electrical energy and contributes to the security of supply. In 2021, it will contribute to 54% of the renewable electricity production and 15% of the total electricity produced thanks to the hydroelectric capacity installed in the countries of the world and to the public financial support granted in this sector.

Other renewable energy sources (wind, geothermal, solar, biomass) have also experienced remarkable growth, with their production multiplying over the last ten years. Even so, the production of renewable energies excluding hydroelectricity is estimated at 40% of the world production in 2021.

The production of wind energy knows a multiplication of 59 between 2000 and 2021 and solar energy marks an increase of 1.1 TWh to 1032.5 TWh during this period.

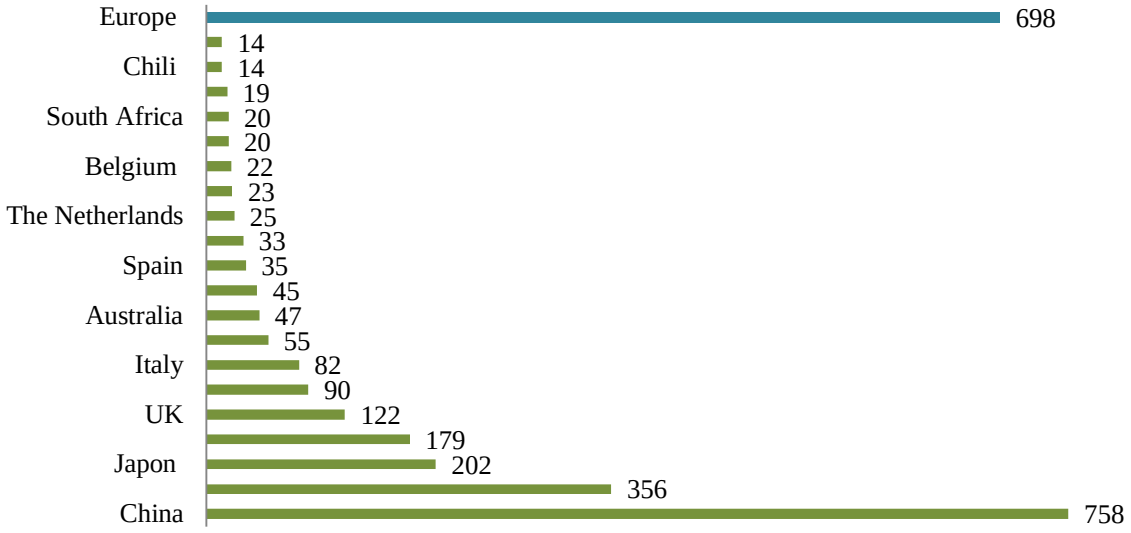
3.2. Global renewable energy investments

The main drivers of the increase in renewable energy in countries around the world are policy support and associated financial commitments from governments (such as feed-in tariffs and long-term power purchase agreements awarded through auctions) and cost reductions. Based on an IEA survey of established national policies and known deployment of new renewable energy projects, the cost of support mechanisms globally in 2017 for renewable electricity is estimated at $143 billion, 2%

higher than in 2016. Wind and solar PV accounted for the majority of non-hydro renewables generation (70% of the total) and were the main beneficiaries of renewable energy support, accounting for over 80% of the total in 2017 (IEA, 2018).

The total amount invested through the first half of 2019 is more than $14 billion. Investment capacity from 2010 to 2019, excluding large hydro, is as shown below in Fig.7 (Frankfurt School-UNEP Centre, 2019, p. 14). China is the largest global investor in renewable energy over the past 10 years, with $758 billion in investment from 2010 to the first half of 2019, ahead of the United States, Japan, Germany, and Italy.

Fig.7: Investment capacity from 2010-2019 ($bn)



Source: (Frankfurt School-UNEP Centre, 2019, p. 14)

China invested about 31% of the total. The United States ranked second with $356 billion in renewable energy investments, Japan third with $202 billion. Europe, meanwhile, made $698 billion in renewable energy investments, with Germany contributing the most with $179 billion, followed by Britain with $122 billion.

The cost competitiveness of renewables has increased over the past 10 years as the average cost of photovoltaics has decreased by 81% and onshore wind by 46% since 2009 due to technology improvements, economies of scale and fierce auction competition. The cost of electricity from new solar PV plants in the second half of 2019 was 83% lower than a decade earlier. Capacity investment in solar slipped 3% to $131.1 billion in 2019, while investment in wind climbed 6% to $138.2 billion. This is the first time the wind surpasse solar in terms of dollars committed since 2010.

During that time, solar investment reached $1.3 trillion, which is half of the total global renewable energy investment of $2.6 trillion.

In addition, in 2018, global investment in renewable energy capacity reached $272.9 billion, three times more than fossil fuel power generation. That year,

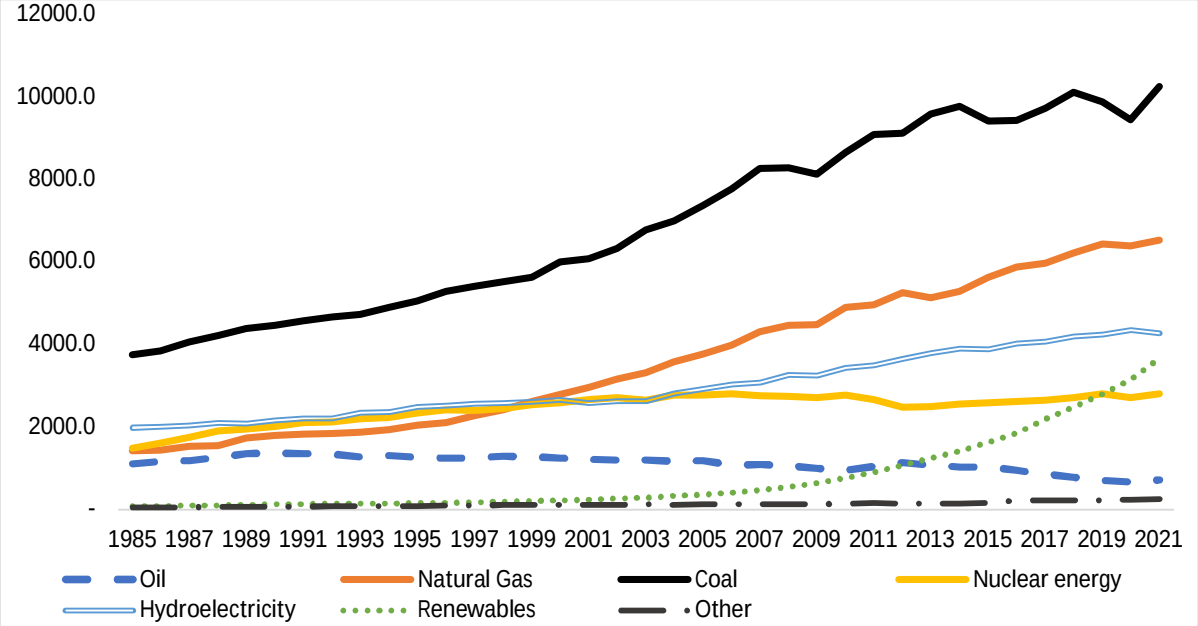
renewables generated 12.9% of total global electricity generation, reducing carbon dioxide emissions by 2 billion tons.

In 2019, renewable energy capacity, excluding large hydro, increased by a record 184 gigawatts (GW) in 2019. This was 20 GW, or 12%, more than the new capacity added in 2018. Yet the 2019, dollar investment was only 1% higher, at $282.2 billion (Frankfurt School - UNEP Collaborating Centre, 2020, p. 5).

3.3. Conventional and renewable electricity generation

According to Fig.8, global electricity production has grown steadily each year since 1974, except between 2008 and 2009, when the global financial crisis caused a significant decline in production. BP's 2020 World Energy Statistical Review indicates that approximately 62.75% of the world's electricity is supplied by fossil fuels.

Fig.8: World Electric Power Generation by Source



Source: based on BP database

The world production of electrical energy increased from 9,879.2 TWh in 1985 to 15,555.3 TWh in 2000. It will reach 28,466.3 TWh in 2021 with a growth rate of 6.2% compared to 2020. The annual growth rate between 2011 and 2021 is 2.5%. Global electricity demand from the 2000s onwards has been growing at 3% per year, faster than total final consumption by two-thirds. Developing economies account for about 85% of this increase. China is the world's largest electricity market with 30% of global production while the United States and India rank second and third (EIA, 2021, p. 252). According to the International Energy Agency (IEA, 2020), electricity generation from all fossil fuels accounted for 57.1% of total gross electricity generation in the OECD until 2019 (compared to 71.7% for non-OECD countries).

Coal is the primary energy source for electricity generation, followed by natural gas and hydro. Electricity from natural gas has more than doubled between 2000 and 2021 recording the annual growth rate of 2.8% between 2011 and 2021. Coal contributed in 2021 to about 35.76% of the total generated, followed by natural gas at 22.9% and hydro with 15%. Renewable energy excluding hydroelectricity has recorded a robust growth of 16.5 since 2011, contributing in 2021 to 12.74% of the electricity produced. Wind and solar power account for a 10.2% share of electricity generation in 2021, the first time these two energies have provided more than 10% of the world's electricity and surpassed the contribution of nuclear. Renewable energies (including hydropower) provided 27% of the world's electricity produced.

4. Electric power production in autonomous grids

Electrical energy is an important driver of socio-economic development in countries. Governments have become involved in the challenge of access to energy in order to ensure reliable electricity supply systems; the design systems ensure better quality of service and security of supply. In this context, long-term sustainable stand-alone electricity projects can help achieve energy access goals and overcome dilemmas

In many regions, community connection to the conventional power grid is restrictive due to financial and geographic factors. In these areas, the electricity delivery is expensive and the maintenance of distribution grids compromise their profitability. The global electrification rate will increase from 83% in 2010 to 85% in 2012 and 90% in 2019.

4.1. Access to electrical energy

In 2019, 10% of the world's population, or 771 million people, have not access to electricity (IEA, 2020). Table 4 shows that, approximately 579 million Africans and 155 million Asians are deprived of this energy, mainly in geographically isolated localities that could not be connected to the national circuit under any circumstances. The poor access to electrical energy and the limitation of electrical consumption in these vulnerable areas that constitute isolated (autonomous) grids. A situation that sees the need to deploy a combination of stand-alone solutions (Bustos & Watts, 2017) in order to improve the coverage of electrical grids.

Table 4: Global electrification rate by region

	Proportion de la population ayant accès à l'électricité					Population without access 2017 (millions)	Population without access 2019 (millions)
	2000	2010	2015	2017	2019		
World	73%	80%	85%	87%	90%	992	771
Africa	36%	44%	49%	52%	56%	603	579
North Africa	91%	>99%	>99%	>99%	>99%	<1	<1
Sub-Saharan Africa	24%	33%	40%	43%	48%	602	578
Developing Asia	67%	79%	87%	91%	96%	351	155
China	99%	>99%	>99%	>99%	>99%	<1	<1
India	43%	68%	79%	87%	>99%	168	6
Indonesia	53%	67%	88%	95%	>99%	14	2
South East Asia	65%	79%	85%	88%	91%	44	36
Developing Asia (other)	38%	58%	73%	76%	79%	125	112
S. cent America	87%	94%	96%	96%	97%	20	16
Middle East	91%	91%	92%	92%	92%	18	19

Source: IEA; Electricity Access Database, (2018, 2019, 2020)

Rigorous progress are made to ensure access to electric power in recent years, with the number of people living without electricity dropping to about 771 million in 2016 from 1.2 billion in 2010. India, Bangladesh, Kenya and Indonesia are among the countries that have made the most progress since 2010. In Indonesia, the electrification rate is over 99%, up from 50% in 2000. In Ethiopia, electricity now reaches 45% of the population compared to only 5% in 2000. The national electrification program has defined a plan to achieve universal access by 2025, aiming to reach 35% of the population with off-grid solutions (autonomous grids).

The global electrification rate reached 89% in the first half of 2019 to reach 90% by 2020 (IEA, 2021). Approximately 153 million people gained access to electricity each year. At least 34 million people in 2017 gained access to basic electricity services through off-grid (stand-alone) technologies.

However, in sub-Saharan Africa and the most remote regions of the world, people still live in darkness, with 579 million Africans lacking access to electricity in 2019. Rural and remote communities are still lagging behind due to the high cost of extending the power grid.

Poor and hard-to-reach areas are not the only ones to use renewable energy. Fossil fuel importing countries set up stand-alone power generation systems to ensure the profitability of their power grids, especially the more isolated ones. The aim is to encourage the development of renewable energy sources and reduce external dependence.

Regions with abundant renewable energy resources provide a unique and appropriate test bed for research and development of the most advanced renewable energy technologies. Some island governments have set ambitious targets for achieving up to 100% renewable energy integration, especially in the islands.

4.2. Autonomous grids as a solution to energy dependency.

Around the world, there are areas where electricity is generated by fossil fuel power plants. The electricity produced is derived from natural gas or diesel. The scarcity of conventional resources has led dependent countries to turn to third countries for their supplies. Energy dependence is based on the different energy resources. The price of imported fuel and the need to transport it make the cost of producing electricity very high. Table 5 bellow summarizes the fossil fuel imports by region.

Table 5: Fossil fuel imports by region

	2011	*2013*	*2015*	*2017*	*2019*	*2021*	*Growth rate per year 2011-2021*
Oil 10^3 of barrel /day							
USA	11338	9859	9451	10148	9094	8478	-2.9%
Europe	12489	12920	13993	14700	14867	13522	0.8%
China	6295	6978	8333	10241	11825	12724	7.3%
India	3823	4370	4380	4920	5379	5325	3.4%
Japon	4494	4637	4332	4142	3779	3350	-2.9%
Rest of world	17634	20012	22026	25663	25980	23559	2.9%
Natural Gas Millions m^3							
USA	94.9	78.6	74.1	83.0	74.8	75.9	-2.1%
Europe	323.6	285.8	270.9	311.9	353.3	341	0.5%
Russia	41.2	32.9	26.5	28.6	26.8	15.1	-9.5%
China	30.5	57.5	73.5	92.8	132.5	162.7	18.2%
India	17.4	18.0	20.0	26.1	32.9	33.6	6.8%
Coal Exajoule (10^{18} joules)							
USA	0.36	0.24	0.28	0.19	0.17	0.15	-8.4%
Europe	5.64	5.85	6.03	5.86	5.25	4.38	-2.5%
China	5.20	7.63	4.69	5.87	6.40	6.54	2.3%
India	2.37	3.66	4.92	5.15	5.69	4.90	7.5%
Japon	4.61	5.06	5.05	5.06	4.90	4.86	0.5%
South Corea	3.38	3.32	3.54	3.89	3.73	3.41	0.1%

Source: BP statistics energy review, 2022

The annual growth rate of world oil imports is about 1.8% between 2011 and 2021. China is the largest importer of oil and natural gas with 19% and 15.9% of world

imports. In 2021, Saudi Arabia and Russia are China's largest oil suppliers with 87.6 million tons and 79.6 million tons. Europe is 21% dependent on foreign oil.

Net oil imports to the United States have decreased by 2.9 million barrels/day compared to 2011; this is due to the development of extraction technologies and production of unconventional oil. Europe imports more than a third of the world's gas. Its main suppliers are Qatar, Russia, Algeria, and Norway. In 2021, Russia account for nearly 40% of Europe's gas consumption (BP, 2022, p. 7), the world's largest exporter, with 1/3 of inter-regional gas trade. The Russian-Ukrainian war has resulted in a vulnerable position for European countries, affecting the European energy sector. Natural gas prices have reached an all-time high, with Germany and Italy depending on Russian gas for more than half of their local consumption (CEPII, 2022, p. 3). The German DIW Berlin Economic Institute has stated that they will face a new gas crisis and that prices will continue to rise leading to increased costs and the entire economy if the conflict worsens and Russia decides to stop deliveries to Germany. Let's remember that Germany has set itself the goal of closing all the country's power plants at the expense of security of supply.

On the coal import side, China is the largest user of foreign coal; almost one-fifth of global imports are Chinese, followed by India, Japan and Korea. In contrast to Europe, European coal imports have decreased by 2.5% between 2011 and 2021.

To counteract this external dependence, fossil fuel importing countries have embarked on renewable electricity generation structures to promote energy efficiency and combat the heavy costs of fossil fuel transportation. Stand-alone grids are a viable solution to promote energy transition and reduce fossil fuel consumption, thereby reducing the conventional energy import bill.

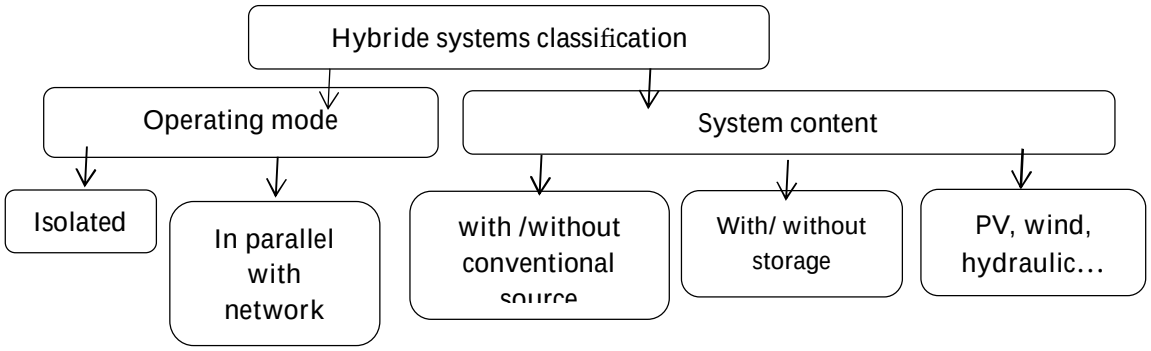
4.3. Conventional and hybrid autonomous grids.

Autonomous grids correspond to production sites that are with non-connection to the main electrical networks. They act independently. Generally, they are characterized by generation capacities that meet local needs. Electricity production in autonomous grids bases on the use of fossil fuels. The integration of renewable energies into autonomous grids characterize a variable production capacity; this variability has the effect of motivating the use of storage, which is why their effective inclusion is complex. In practice, storage is only rarely used since the few systems that provide appropriate performance for the operation of autonomous grids are either very expensive to install, such as solar towers, or have a limited life span, such as batteries.

Grids consisting of at least one renewable energy source coupled with a conventional (thermal) energy source or multiple renewable energy sources with or without conventional energy sources operating in stand-alone or grid-connected mode are referred to as hybrid renewable energy systems (Bajpai & Dash , 2012) as shown

in Fig.9. These hybridization systems have become widespread for stand-alone power generation in remote locations due to technological advances in renewable energy and power electronic converters that are used to convert unregulated energy generated from renewable sources into useful energy at the end of load as shown in Figure 10. The important feature of hybrid renewable energy systems is that they combine two or more renewable and conventional energy generation technologies to make the most of their operations and achieve higher efficiencies than could be achieved from a single energy source. They can address limitations in terms of fuel flexibility, efficiency, reliability and energy savings.

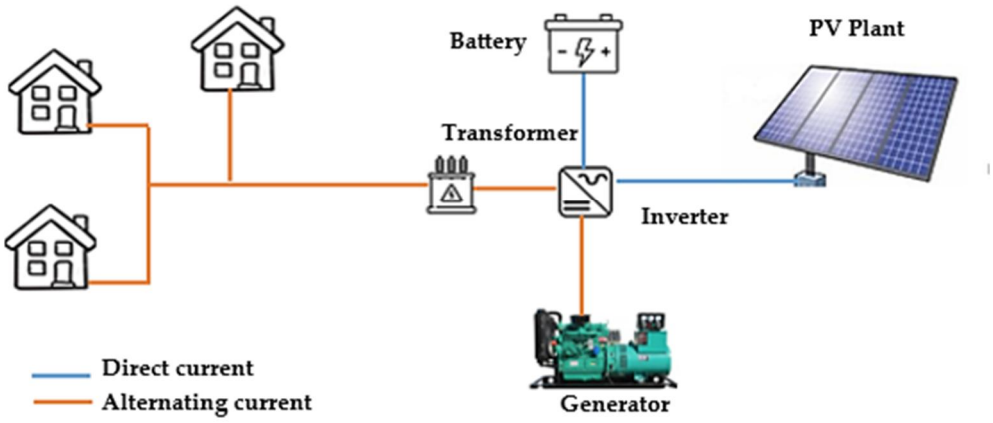
Fig.9: Classification of hybrid systems



Source: *(Stoyanov, 2011, p. 25)*

Hybrid systems with renewable energy sources and/or conventional power generation are either grid-connected or grid-isolated. The energy potential available at the site is an important criterion for the selection of the source used. It depends on the location of the hybrid system. Hybrid power plants with storage contain a storage battery sized to store surplus energy (fig.10). A stand-alone hybrid power plant without storage requires rather low investment costs.

Fig.10: Schematic diagram of a PV-diesel hybrid system for stand-alone electrification



Source: constructed by the authors

The hybrid renewable energy system offers the possibility of meeting demand for several hours during the night thanks to the battery. The installed PV capacity can cover partially or completely the day's electricity demands. The diesel generator is often used to cover the evening peak power demand to ensure full recharging of the batteries.

Since photovoltaic panels produce direct current (DC) and the grids operate on alternating current (AC), the heart of a hybrid system is an inverter. The inverter supplies the direct current energy produced by the photovoltaic and provide it is to the grid after its conversion to alternating current. The inverter also controls the production and storage systems.

The implementation of such a system aims to diversify the sources of renewable energy and to reduce the amount of fuel consumed since the renewable sources can complement each other and provide a greater amount of energy. The hybrid systems ensure a safe, better quality and improved efficiency of the system operation (Saheb & Belhamel, 2007, p. 3)

5. Conclusion

Faced with the probable fossil fuels scarcity and the volatility of energy prices, energy-intensive models based on the continuous consumption of energy are accused of contributing to the depletion of fossil fuels. The global context characterized by both geopolitical uncertainties and the sharp increase in energy consumption (+51% between 1999 and 2019 and more than 202% between 1969 and 2019), particularly in connection with the growth in demand from emerging countries, has required a new reflection on the use of conventional resources.

Diversification of energy sources decreases energy dependence and offsets rising fuel prices by reducing operating costs to the extent that it provides a better quality of service than conventional systems based on a single source of electricity generation.

The unprofitability of conventional power grids in countries poorly endowed with fossil resources and communities whose access to electricity is difficult, has pushed towards the adoption of autonomous grids to generate electricity by developing electrical systems based on non-conventional sources to ensure security of supply and improve the socio-economic conditions of the populations. The integration of renewable resources in stand-alone power systems considerably alleviates the problems of electrification of sparse and remote areas, which cannot aren’t connected to the main grid for economic reasons and external dependence.

The intermittency of renewable energies and the problem with the variable and non-guaranteed power produced by these energy sources is resolved on coupling the supply sources and forming hybrid renewable energy systems. The latter, which has gradually become a viable economic solution on an international scale, optimizes the yields of autonomous grids and favors energy storage, which ensures better satisfaction

of electrical loads during periods of absence of a primary resource to convert into electricity

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