The increasingly important role of decentralized solar energy in Morocco

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Abstract
To our knowledge, they were no detailed numbers published recently on decentralized solar energy in Morocco, even if it starts to gain importance. In the country, demand for photovoltaic solar modules has experienced three major phases: a long period of "relative gloom" (1995-2010) between two phases of rapid growth (1985-1995 and 2010-2018). Today, the inevitable acceleration of solar PV systems connected to the grid has become a reality, despite the absence of any regulation in a legislative framework that has become permissive. It is increasingly urgent to adopt an Application Decree of the net-metering approach to encourage subscribers to declare their solar PV installations to allow verifying that the installed inverters are of sufficient quality and that they do not send unwanted harmonics in the network. At the same time, butane gas, in addition to its use in cooking, is widely preferred for heating domestic water, because of the subsidy. This subsidy is unfair competition to solar water heaters and should be removed because it greatly benefits the richest quintile of the population [1], slightly increases Morocco's energy dependency by pushing for the waste of so cheap butane gas and surely encourages its use in pumping for agricultural irrigation.

Keywords: Morocco; dispersed solar photovoltaics; dispersed solar thermal; sales; employment; contribution to the energy and greenhouse gas savings.

Highlights:
• We remind the history of energy and electricity in the Moroccan energy balances
• We highlight the increasing importance of decentralized solar energy not in the national balances
• We estimate business, employment, and electricity generated as well as greenhouse gases savings
• We situate the Morocco position in the world in terms of the level of solar equipment
• We propose two courageous actions to accelerate the development of decentralized solar energy.
1. Introduction
Morocco initiated in 2009 a transition to a greater appeal to local resources, in particular, solar and wind energy essentially, but not only, because he is among the ten highest energy-import dependent countries [2]. Despite this, its energy intensity is not only better than all the energy-import dependent countries but also than the majority of the others [3]. However, one of the greatest attractions of the so-called "decentralized energy" is, precisely, that, by not entering into the national accounts, it contributes to improving the apparent energy intensity of the country. If only for that, they deserve to be supported and encouraged, which, as we will see, is not the case in Morocco, hence the importance of the work that we present.

1.1. Morocco national energy balances

1.1.1. Energy demand in the national energy balances
Figure 1 shows the evolution of the energy demand together with its growth (left graph) and of its structure (right graph). It has been plotted using figures arising from official sources [4,5].

Morocco energy demand will multiply by almost 5.5 in forty years (1980-2020) after having gone through two faster growth periods (at 5.5 to 6% per year) centered in 1992 and 2008, while, during the same period, the population multiplied by 1.85, much less than the energy demand increase. The growth of the electricity and the butane gas shares comes at the expense of other components notably that of other fuels for thermal uses, which include propane and the part of fuels not used for the production of electricity (coal, natural gas, fuel, and diesel).
Figure 2 shows the evolution of butane subsidy figures. The left scale is intended for the total subsidy while the right scale is for the subsidy per kg.

**Figure 2** Butane gas subsidy in Morocco [6]: total (in blue and left scale) and per kg (in red and right scale).

Figure 2 gives also an idea of the impact of the butane gas subsidy as well as its weight on the national economy by exceeding 1.7% of GDP.

### 1.1.2. Electricity demand in the national energy balances

Figure 3 shows the evolution of the net electricity locally injected (left graph) and of its structure (right graph).

**Figure 3** Left graph: Electricity injected into the grid and its growth - Right graph: Its constitution
Net electricity injected in the Moroccan grid will multiply by almost 8 in forty years after having gone through two faster growth periods (6.5 and 7% per year) centered in 1987 and 2008, while, during the same period, the population multiplied by 1.85. The shares of the different sources of electricity production have varied very substantially at each commissioning of a new power plant: what is structural, is the slowdown of the use of petroleum fuels for electricity production, and more recently the reduction in imports and the acceleration of the use of renewable sources (wind and solar).

1.2. Some technical details about decentralized solar energy

1.2.1. Solar radiation in Morocco

Figure 4 shows two maps of Morocco colored according to the incident solar radiation: on a horizontal surface for the left map or on a facing South surface tilted at 30° for the right map. These maps are the ones that were used in reference 7.

![Solar radiation maps](image)

Figure 4 Solar radiation incident on a horizontal plane (left) and facing South tilted at 30° (right)

The yearly average of the daily solar energy is around 4.8-5.3 kWh/m² in the most northern regions of Morocco while it climbs to 6.3-7.0 kWh/m². Thus, a surface facing south and tilted at 30° from the horizontal plane:
- solar PV, with an efficiency of 14%, can generate between 269 and 356 kWh/m².year of electricity,
- solar thermal, with an efficiency of 40%, can generate between 770 and 1,017 kWh/m².year of heat.

Even in the most northern regions of Morocco, solar radiation still gives interesting yearly energy productions.

### 1.2.2. Photovoltaic solar energy

Photovoltaic (PV) modules are made of solar cells mainly encapsulated between glass and plastic. They produce a direct electric current proportional to the solar radiation they receive and are characterized by the electrical direct power they deliver under ideal laboratory conditions, known as "STC". The power obtained under these STC conditions is then expressed in peak-Watt (Wp). The price of the peak-Watt drives the global market for solar photovoltaic modules, which are used for:

- **Pumping**: For water pumping, the PV modules connect the pump to the modules via a converter whose output must be adapted to the type of electric motor pump (AC or DC) and water is often stored in a reservoir. Solar pumping facilities exist in Morocco since 1985 and especially their size and quantity have increased sharply over time through lower prices for PV solar modules.

- **Autonomous electrification**: When electrical power requirements are not in phase with the sunlight, electricity is stored in batteries (12Vdc or multiple), which recharging is controlled by a regulator. This storage considerably increases the price of electricity but makes it available anywhere independently. When ac is needed (230Vac or 380Vac), an inverter converts the direct current. The so-called "autonomous" inverters must be powered by batteries and provide power on demand. Autonomous electrification installations of remote sites (dwellings or telecommunication antennas) have existed in Morocco since 1985. Their market share is shrinking because of the territorial extension of the Moroccan electric grid under the Global Program for Rural Electrification (PERG), which now serves over 99% of the rural population, with a rural subscription rate of 82% in 2018.

- **Grid power**: To inject electricity in an electric grid (before or after the distribution company energy meter), PV modules electricity goes through a "synchronous" inverter which converts the DC to AC proportionally to the received solar radiation while adapting in voltage and in phase with the power grid to which it is connected. These "synchronous" inverters convert solar systems to a mini-electric plant, which can have an installed capacity ranging from a few hundred Wp to several hundred MWp (millions of Wp). In Morocco grid-connected solar installations only started very timidly in 2006, but their market share became dominant thanks to the reduction in amortization times induced by the sharp fall in both solar PV modules and synchronous inverters prices. Some farmers feed partly their grid-connected ac pumps with a grid-connected PV plant. All the possibilities offered for self-consumption are already operational.
1.2.3. Solar thermal energy

In the thermal collectors which equip the solar thermal installations (STI) a "heat transfer fluid" (sometimes a phase change liquid, but in most cases water mixed or not with an antifreeze liquid) circulates in tubes that are welded to a black "absorber" that absorbs more solar radiation than what it emits. The assembly formed by the tubes and the absorber is mounted inside a collector box, a "greenhouse" which front facing the sun is glass and the remainder is thermally insulated from the outside (either by an insulating material for the flat-plate collectors or through a vacuum for the tubular collectors). Spontaneously, the heat generated tends to emerge towards the top of the collectors (thermosiphon) and the simplest is to place a hot water tank above the collector(s). If necessary, a circulation pump forces the "heat transfer fluid" leaving the solar thermal collectors to descend towards a tank, which would be located below the position of the collector. Although there are wide disparities, the price per collector m² drives the global market of solar thermal collectors, which split into two families:

- **Glazed collectors (either flat-plate or tubular):** Both produce heat energy which varies with incident solar radiation and both achieve the appropriate temperatures to heat or preheat water for domestic use or space heating (40-70°C). Because of a loss of light transmission against better insulation, tubular collectors have better efficiency in colder regions (like northern Europe) while the flat-plate ones are more effective in temperate regions (like Southern Europe and North Africa). Solar thermal systems exist in Morocco early eighties.

- **Unglazed flat-plate collectors:** Despite the better light transmission, the absence of glazing loses the greenhouse effect, thus, unglazed flat-plate collectors can only achieve temperatures required by swimming pools (25 to 28 °C).

The market of solar air heaters is much more limited and, to our knowledge, almost inexistent in Morocco.

1.3. Legal and Regulatory background of renewable energies in Morocco

Law 57/15 was promulgated on 2015 to amend the initial Law 13/09 on renewable energies adopted on 2009: in fact, both are laws on production of electricity from renewable sources. Almost ten years after Law 13/09, the Regulatory framework is still far from being complete:

- Decree 2657-11/2011 is devoted to areas intended to accommodate large wind farms but there is still no decree fixing the deployment areas of large solar farms.
- Law 13/09 already allowed access to the medium-voltage (MV) grid and Decree 2-15-772 /2015 fixes the conditions for it. However, some decisions concerning access to the MV grid have been delegated to the National Authority for the Regulation of Electricity (ANRE), created in 2015 by Law 48/15 relating to the regulation of the electricity sector, but ANRE has still not taken any decision on this.
- A Decree regulating the access to the low voltage (LV) grid still does not exist, even if the Law 57/15 allows it.

With Law 54/2014, which raised the power ceiling from 50 to 300 MW, it seems, at the bottom line, that everything has been done for the massive production of wind and solar electricity and still
practically nothing for the decentralized production of photovoltaic solar electricity, and that, despite this, solar PV is developing.

Based on Law 47/2009, which established the Energy Efficiency Guidelines in Morocco, several Application Decrees have been promulgated but are still not executed like:

- The Thermal Regulation of Constructions (RTBM Decree 2-13-874/2014),
- The Regulation relating to Compulsory Energy Audits and Audit Bodies (Decree 2-17-746/2014),

Some other Decrees are expected to come, they concern:

- Energy Service Companies (Project of Decree 2-18-165/2019 on ESCOs),
- Energy performance and labeling of devices and equipment,
- Energy impact study (for public buildings),
- Technical control (Control of compliance with Energy Efficiency Regulations).

No help is coming soon for solar water heaters and the "Shemsi” National Program for the Development of Solar Water Heaters is even still described as a "concept" on the official website of the Moroccan Agency for Energy Efficiency (AMEE).

At the bottom line, we can say that decentralized solar energy is now growing mostly without help.

1.4. Bibliography and scope of this paper

We did a fast survey of the indexed review and research articles on energy in Morocco, as a country; its summary is shown in Table 1.

In another work\textsuperscript{12}, we already commented few additional papers devoted to the income-energy nexus.

In fact, out of the fifteen papers of Table 1:

- Five[8,9, 10, 11, 12] were devoted to the capacities of the country to generate energy from such or such solar or wind technology,
- eight others have studied different aspects of the Moroccan National Energy Strategy, considered from the energy forecast point of view, governance\textsuperscript{13} and generation of centralized renewable electricity[14, 15, 16, 17, 18, 19]
- the two lasts [20,21] focused on fossil fuels without even taking an interest in solar energy, which we will be talking about here.

To our knowledge, they were no detailed numbers published recently on decentralized solar energy in Morocco, even if it starts to gain importance. We are interested in decentralized energy because it is an invisible part of the national energy accounts. We focus on solar energy because we think it is becoming a dominant component of decentralized energy. In this paper, we intend to assess the size of the decentralized solar energy markets in Morocco (photovoltaic and thermal solar), their yearly energy generation as well as various socio-economic (like sales and employment) as well as environmental impacts (like avoided emission of greenhouse gases). The evolution is studied from its earliest stages (eighties). The objective of this work is to support feasible recommendations for the development of this decentralized solar energy in Morocco, which costs nothing in public money.
Table 1 Summary of recent bibliography of indexed papers on energy in Morocco

<table>
<thead>
<tr>
<th>Ref</th>
<th>Year</th>
<th>Content</th>
</tr>
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<tbody>
<tr>
<td>7</td>
<td>2018</td>
<td>Yield of solar photovoltaic over Morocco</td>
</tr>
<tr>
<td>8</td>
<td>2017</td>
<td>Yield of solar water heating over Morocco</td>
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<tr>
<td>9</td>
<td>2015</td>
<td>Yield of solar water heating over Morocco</td>
</tr>
<tr>
<td>10</td>
<td>2015</td>
<td>Yield of solar air-conditioning and its specific cooling costs over Morocco</td>
</tr>
<tr>
<td>11</td>
<td>2019</td>
<td>Evaluation of the wind energy potential as a power source in Morocco’s regions</td>
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<tr>
<td>12</td>
<td>2016</td>
<td>Forecasts of the energy consumption of Morocco towards 2030 using different models</td>
</tr>
<tr>
<td>13</td>
<td>2011</td>
<td>Assessment in the MENA region of the potential advantages and merits of international and regional institutions, initiatives and financial mechanisms dedicated to the promotion of renewable energies</td>
</tr>
<tr>
<td>14</td>
<td>2015</td>
<td>Quantification of the optimal combination of Renewable Energy Resources to assess the NES power generation mix from a meteorological perspective</td>
</tr>
<tr>
<td>15</td>
<td>2014</td>
<td>Assessment of past contributions of different factors, including the supply mix, to the fuel requirements in the thermal power generation and forecast to 2020</td>
</tr>
<tr>
<td>16</td>
<td>2019</td>
<td>Critical, multiscalar and multidisciplinary approach to examine the Moroccan Solar Plan</td>
</tr>
<tr>
<td>17</td>
<td>2012</td>
<td>Simulation of the macroeconomic impact of the foreign investment inflows needed to make available the installed capacities related to RES demand scenarios for Morocco</td>
</tr>
<tr>
<td>18</td>
<td>2015</td>
<td>Status of the energy sector and its future challenges in Morocco: review and discuss of the recent government strategies putting the transition to renewable alternatives on the top of the national policy, implications for energy security and low-carbon economy</td>
</tr>
<tr>
<td>19</td>
<td>2017</td>
<td>Avoiding defining energy security as independence from reliance on external hydrocarbon fuels, the work gives arguments for utilizing a multidimensional energy security framework by evaluating perceptions of the energy security for electricity integration for Morocco</td>
</tr>
<tr>
<td>20</td>
<td>2018</td>
<td>Use of a cointegration approach to study the impact of oil prices on the Moroccan utility electricity production and estimation of the elasticity of the electricity produced, by different fuel sources (coal, oil, and water), to oil prices</td>
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2. The Moroccan decentralized solar market

2.1. Solar photovoltaic market

The blue squares of Figure 5 show the evolution of the wholesale price of photovoltaic modules (in Moroccan Dirhams, Dh per Wp). These blue squares of Figure 5 were obtained from the ex-works prices given by Ken Zweibel [22], increased by 5% to estimate freight and insurance costs before converting to the Moroccan Dirham at the average exchange rate of the year (red curve related to the right scale of Figure 5).
Figure 5 Peak-Watt prices of photovoltaic modules (in Dh per Wp)

On a scale of 30 years, Figure 5 shows that:
- Prices in Dh / Wp, Cost Insurance and Freight (CIF, blue squares of Figure 5) fluctuated by ± 25% (blue vertical bars of Figure 5) around a regularly decrease of almost 9.5% per year (decreasing blue curve Figure 5). This decrease results from a so-called learning curve "Swanson Law" which shows that the global solar PV prices fall by nearly 20% every time the cumulative global sales of dual 22,23,24].
- Thus, PV local CIF prices have been divided by 15 over thirty years.
- This price fall has made the solar PV electricity cost better than conventional power generation means and often much more profitable [25]

Figure 6 shows the evolution of the peak power (expressed in MWp, million of Wp) installed annually in Morocco (black squares) and cumulative (blue circles). Data for Figure 6 was obtained by dividing the CIF values of imports data from the Exchange Office [26] by the unit prices of Figure 5 and removing the big PV plants that already count in the national energy balance sheets [27]. Since the values vary by more than four orders of magnitude, the ordinate of Figure 6 is in a logarithmic scale (vertical tile for each multiplication by 10) to display variations that are not visible on a normal scale.

Figure 6 Rated power installed annually in Morocco (black squares) and cumulative (blue circles)

On a scale of 30 years, Figure 6 shows that:
- Demand grew quickly until 1995 (almost 80 times in 5 years). This first phase is characterized by the arrival of solar PV in a country whose rural electrification rate is below 18% and
without any important rural electrification program. Almost all installations were then autonomous and had low rated power (mainly less than 50 Wc).

- Demand grew less rapidly between 1995 and 2010 (almost 3 times in 15 years), the Global Rural Electrification Program (PERG), with its arrival promises of the electricity grid, put a brake on the spontaneous demand from non-electrified remote areas of the country. However, the PERG has also integrated a solar component that has helped to feed with solar PV installations autonomous 51,509 (1998-2008), then 19,438 homes (2014-2016) combining nearly 8 MWp.

- The demand has again grown very rapidly since 2010 (almost 100 times in 8 years). During this third phase, standalone PV solar electrification became a minority. Driven by the falling prices, the PV solar pumping systems take over, gradually overwhelmed by the grid-connected systems, ending the times where the PV modules were visible only in remote areas.

2.2. Solar thermal market

Figure 7 shows the evolution of wholesale prices for thermal collectors (in Dh per m²). Figure 7 was obtained from the CIF value of imports and masses imported annually[26], with a constant mass per m² collector.

![Figure 7](image)

**Figure 7** Unit wholesale prices of thermal collectors (Dh per m²)

Solar thermal has reached a maturation phase and no longer suffers "learning-curve". On a scale of 30 years, Figure 7 shows that:

- Prices in Dh/m² Cost Insurance and Freight (CIF blue diamond Figure 7) fluctuated by ± 15% (blue vertical bars of Figure 7) around a very slow decrease of nearly 0.34% per year (decreasing blue curve Figure 7).

- Thus, prices have lost 5 to 6% in thirty years, which is very low but still significant given the increasing purchase power in the meantime.

- The thermal energy produced by the solar collectors has always been more profitable than that delivered by the Moroccan electricity distributors. Even very modest, this drop in prices combined with the rise in electricity prices has made thermal solar even more attractive but, although "fair play", this competitiveness goes unnoticed by the formidable rival that is the heavily subsidized butane gas. Indeed, the withdrawal of subsidy of the 12 kg bottle places its price around 120-140 Dh and not the present 40 Dh[28]. Because of this, in Morocco, a solar
water heater pays for itself in about 10 years against butane gas, net of the benefits related to comfort and safety, while the pay-off is around 5-6 years against electricity or propane gas.

Figure 8 shows the evolution of the area (in m²) installed annually in Morocco (black squares) and cumulative (blue circles). Figure 8 is calculated from the CIF values of imports data from the Exchange Office and the m² prices of Figure 7. Since the values vary by more than 2 orders of magnitude, the ordinate of Figure 8 is in a logarithmic scale (vertical tile for each multiplication by 10) to display variations that are not visible on a normal scale.

Figure 8 shows that the annual demand has practically been multiplied by 20 in 25 years with an average growth of nearly 11% per year, which is not very fast compared to the growth of Moroccan photovoltaic modules demand (see Figure 6). It is even surprising that the demand kept increasing for such a long period, despite the tough competition of butane gas.

3. Decentralized solar energy in Morocco and business

3.1.1. Decentralized solar photovoltaic and business

Figure 9 represents the evolution of the estimated installation sales of the solar PV sector in Morocco. Since the values vary by more than 2 orders of magnitude, the ordinate of this Figure 11 is also in logarithmic scale (vertical tile for each multiplication by 10) to display variations that are not visible with a normal scale. Figure 9 was obtained by considering that the cost of the year's modules represents only 40% of the price charged to the final end-user, to allow space for a margin and cost of balance of systems (stands, brackets, cables, cases, accessories and any other equipment such as variable speed drives, inverters or batteries with charge controller).
Thus, the sales would have:

- increased very rapidly until 1995 (6-fold increase in 5 years)
- slightly decreased while strongly oscillating between 1995 and 2011,
- increased sharply since 2011 (60-fold increase in 17 years) to exceed 5 billion Dh in 2018.

With a value-added rate of about 20% and apparent employment productivity around 90,000 Dh 2008\(^{[31]}\) (updated to 1.5% per year), we reach the following conclusions:

- PV solar system installations have contributed to the creation of a few tens of jobs until 1993,
- from there, the number of jobs created amounted to a few hundred until about 2015,
- since 2016, thousands of jobs were created and ten thousand should probably be reached by 2020.

These figures do not include the jobs needed for solar PV in operation and resulted in almost 25 jobs per yearly installed MW\(_p\).

Figure 9 represents the evolution of the production of electricity by systems having less than 20 years old (blue and referring to the left scale) and the percentage of produced electricity they represent (in red and referring to the right scale). Since the values vary by more than 3 orders of magnitude, both ordinates of this Figure 10 are, also, in a logarithmic scale (vertical tile for each multiplication by 10) to display variations that are not visible with a normal scale.

**Figure 9** Installation turnover (in MDh) and jobs of the PV solar sector in Morocco

**Figure 10** Local grid-electricity avoided by decentralized PV (blue, left scale), its share (red, right scale)
The red curve of Figure 10 increases because the solar photovoltaic capacity grew much faster than the electricity produced in Morocco:

- From 0.04 thousandths of the electricity generated in 1990, the share of solar PV increased to 4 thousandths in 1995. Then, this share rose from 4 to 12 thousandths between 1995 and 2010. Finally, electricity produced by the PV solar rose to 2.2% of the electricity generated in 2018.

is, in thirty years, multiplying by 200 in value ... and 500 in relative contribution.

- The recent figures contribute surely to the alleviation of the growth of national demand for electricity after 2015[29].

3.2. Solar thermal and business.

Figure 11 represents the evolution of the estimated installation sales of the solar thermal sector in Morocco. The ordinate of Figure 11 is also on the logarithmic scale (vertical tile for each multiplication by 10) to display variations that are not visible on a normal scale. Figure 11 was obtained by considering that solar thermal installations (STIs) are sold to the final end-user at 3,500 Dh per m² of collector (VAT excluded) [30]. This takes into account a margin and the costs of other parts of the solar thermal systems (tank, pedestals, stands, piping, accessories and eventual other equipment such as differential thermal regulators and circulation pumps).

Thus, the sales (blue circles Figure 11) would have:

- increased, multiplied by 10 to 15 in two decades
- almost stagnated since 2015 around 500-540 million Dh.

With a value-added rate about 20% and apparent employment productivity around 90,000 Dh 2008 [31] (updated to 1.5% per year), we reached the following conclusions:

- the number of jobs in solar thermal installations was in tens of jobs until 2007,
- from there, the number of jobs created amounted to a few hundred until about 2018 and seems to stagnate around a little more 200.

These figures do not include the jobs needed for solar thermal maintenance and resulted in slightly more than 0.7 jobs per yearly thousand of installed collector square meters.

Figure 12 represents the change in the structure of the installed surface in Morocco. Domestic solar water heaters (DSWH, kits including collector(s), connecting pipes and tank) have always dominated
the Moroccan market and tend to dominate more and more to over 80% after going down around 75% the middle of the 2000-2010 decade, probably at the instigation of PROMASOL program that was driven by CDER (now became AMEE, Agency for Energy Management and Efficiency).

Figure 12 Market structure of the cumulative installed surface in Morocco.

Figure 13 shows the evolution of electricity generation avoided by the installed solar thermal plants (blue and referring to the left scale) and the share of electricity production that they represent (in red and referring to the right scale). Both ordinates of Figure 13 are on a logarithmic scale (vertical tile for each 10-fold increase) to display variations that are not visible on a normal scale.

The red curve of Figure 13 increases because the solar thermal capacity grew much faster than the electricity produced in Morocco:

- From 3 ten-thousandths of 1990 electricity generated in 1990, the share of solar thermal has risen to 14 ten-thousandths in 1995 (0.14%). Then, this share gradually increased for more than 20 years to reach 1.21% in 2018 is, in thirty years, multiplying by 8 the relative contribution.

If a butane gas combustion efficiency of 60% is considered, the 452 GWh of useful energy generated by the solar thermal heaters in 2018 accounted for 752 GWh or 65 ktoe of butane gas which still accounts for only 2.5% of country needs of butane gas (2'558 ktoe, based on 2,343 million tons,
extrapolated to 2018 from older values 2017 [32]). It is realistic to consider that the potential is at least five times the present installed surface area, more than 4 million square meters of collectors.

4. Power and energy impact of decentralized solar energy in Morocco

Figure 14 shows the evolution of (i) the yearly grid-load maximum power (blue squares related to the left scale), (ii) the equivalent of electric power generated at noon by the decentralized solar energy plants (blue triangles related to the left scale) and (iii) the percentage that the seconds represent in the firsts (red diamonds related to the left scale). Both ordinates of Figure 14 are on a logarithmic scale (vertical tile for each 10-fold increase) to display variations that are not visible on a normal scale.

![Figure 14](image-url)

**Figure 14** The impact of decentralized solar plants on the yearly peak demand for electricity.

Powers generated by the decentralized solar PV and thermal installations, shown in Figure 14, are calculated based on the following conservative hypothesis:

- decentralized solar PV, 70% of performance ratio, e.g. 700 W per kWp installed,
- decentralized solar thermal, 500W per collector square meter.

With these conservative hypothesis, the decentralized solar installations have saved regularly increasing shares of the yearly maximum power from 0.2% (2.5 MW in 1990) to 12.6% (793 MW in 2018), which is even more than the power available at the output of the Ouarzazate NOOR Complex cumulating 580 MW (troughs, tower, and centralized PV).

Figure 15 shows the evolution of (i) the yearly net injected electric energy (blue squares related to the left scale), (ii) the equivalent of electric energy generated by the decentralized solar energy plants (blue triangles related to the left scale) and (iii) the percentage that the seconds represent in the firsts (red diamonds related to the left scale). Both ordinates of Figure 14 are on a logarithmic scale (vertical tile for each 10-fold increase) to display variations that are not visible on a normal scale.
Energy generated by the decentralized solar PV and thermal installations shown in Figure 15 is aggregated from Figure 10 and Figure 13. The decentralized solar installations have saved regularly increasing shares of the yearly electricity needs from 0.02% (2.9 GWh in 1990) to 4.07% (1,591 GWh in 2018), which, again, is about 150% of the energy yearly generated by the Complex NOOR of Ouarzazate. Decentralized solar energy indeed took 30 years to achieve this but it also true that two-thirds of this path were attained in the last five years.

5. Environmental impact of decentralized solar energy in Morocco

5.1. The environmental impact of solar photovoltaic in Morocco

Figure 16 shows the evolution of greenhouse gases greenhouse avoided by operating photovoltaic plants for 20 years (blue referring to the left scale) and what they represent in comparison with emissions from the electricity produced in Morocco (red referring to the right scale). Since the values vary by more than 3 orders of magnitude, both ordinates of Figure 16 are in a logarithmic scale (vertical tile for each multiplication by 10) to display variations that are not visible on a normal scale.
The greenhouse emissions factor of electricity produced in Morocco is not constant. While continuing to grow rapidly (nearly 40% per year), greenhouse gases avoided by solar power PV grew slightly above one million tons of CO₂ equivalent in 2018 and help to reduce 3.4% of the emissions of greenhouse gases from the electricity produced in Morocco.

5.2. The environmental impact of solar thermal in Morocco

Figure 17 shows the evolution of gas emissions greenhouse avoided by solar thermal (blue referring to the left scale) and the percentage they represent in the emissions of electricity produced in Morocco (red referring to the right scale). Since the values vary by more than 2 orders of magnitude, both ordinates of Figure 17 are in a logarithmic scale (vertical tile for each multiplication by 10) to display variations that are not visible on a normal scale.

Figure 17 Greenhouse gases avoided by solar thermal (blue, left scale) and its share of avoided electricity production emissions (red, right scale)

While continuing to grow moderately in 1995 (nearly 16% per year), greenhouse gas emissions avoided by solar thermal slightly exceed, in 2018, 0.4 million tons of CO₂ equivalent and contribute to reducing 1.47% of greenhouse gas emissions of the electricity produced in Morocco.

6. Morocco's solar energy in the world

6.1. Morocco's solar photovoltaic energy in the world

It is helpful to visualize what the installed capacity of Figure 6 represents globally. Thus, Figure 18 shows the evolution of cumulative peak power installed worldwide (blue and referring to the left scale) and that of the part of Morocco in this total (red and referring to the right scale). The blue curve of Figure 18 was obtained based on figures from the European Photovoltaic Industry Association[33] (EPIA), Solar POWER Europe[34] and REN21[25]. Since the values vary by more than 3 orders of magnitude, both ordinates of Figure 18 are in a logarithmic scale (vertical tile for each multiplication by 10) to display variations that are not visible on a normal scale.
It is clear that, for a short period, Morocco has been a good country choice for PV, accumulating nearly 1/22nd of modules sold worldwide (4.8% of the total installed capacity in the world in 1996). Then, this position has gradually deteriorated and Morocco has lost many places in the world ranking after getting down to less than 1/1000th of the modules sold worldwide (0.08% of the total installed capacity in the world 2011). Since then, the rapid growth seen in Figure 8 allowed catching up, and Morocco has exceeded 0.7% of the total installed capacity in the world in 2018.

Another way to make Morocco Benchmarking in the world is to compare the level of solar photovoltaic equipment (installed power per capita) compared to the world average. This is shown in Figure 19 whose ordinate is also in logarithmic scale (vertical tile for each multiplication by 10) to display variations that are not visible with a normal scale.

The analysis of the evolution over time shows that Morocco's equipment level was above the world average until 2007, he descended to become 6 times smaller than the latter in 2011 (0.715 to 4.33 Wp/inhabitant) to rise again above the global average in 2018. Although in 2014, Morocco is not included in the "top ten" of best countries in terms of installed capacity, it is mapped since 2017 in the third group of countries (out of five), those with between 10 and 100Wc / capita.

Figure 20 shows some of the best prices of recent contracts PV solar power purchase worldwide [25].
Best solar PV electricity power purchase agreements (in MAD/kWh)

Figure 20 Map showing examples of the best solar PV power purchase prices until the end of 2017.

The price for Morocco is that of awarding NOOR 4 PV plants (Ouarzazate, Laayoune, and Boujdour).

Note that prices do not depend only on country sunlight.

6.2. Morocco’s solar thermal energy in the world

It is helpful to visualize what the installed capacity of Figure 8 represents globally. Thus, Figure 21 shows the evolution of accumulated surface installed worldwide (blue and referring to the left scale) and that of the part of Morocco in this total (red and referring to the right scale). The blue curve of this Figure 21 was obtained based on figures from the Solar Heating and Cooling Program (SHC) of the International Energy Agency (IEA)\textsuperscript{34, 35} and those of REN21\textsuperscript{36}. Both ordinates of Figure 21 are in a logarithmic scale (vertical tile for each multiplication by 10) to display variations that are not visible on a normal scale.

Figure 21 Installed solar thermal worldwide (blue, left scale) and the Moroccan share (red, right scale).

The Moroccan contribution to the world installed solar thermal capacity is low but remained stable, around 0.10\%, for three decades. This means that the growth seen in Figure 8 was approximately parallel to the global evolution.

Another way to make Morocco Benchmarking in the world is to compare the level of solar thermal equipment (installed surface for 1,000 inhabitants) compared to the world average. This is shown in
Figure 22 whose ordinate is also in logarithmic scale (vertical tile for each multiplication by 10) to display variations that are not visible with a normal scale.

The analysis of the evolution over time shows that the level of Morocco's equipment has always been about 4 times smaller than the world average. This means, in particular, the level of equipment remained parallel at global equipment. Despite its sunshine, Morocco is still not included in the "top ten" solar thermal countries but it is still listed in the third group of countries (out of five), those with between 20 and 70 m² per 1,000 inhabitants [37].

Figure 23 shows the Mediterranean countries that were placed ahead of Morocco in 2016.

The values were extracted from the summary of the last Report [38] of the European Federation of Solar Thermal Industry (ESTIF).

7. Conclusions
Decentralized solar energy production (Figure 10 and Figure 13) is not taken into account in the national balance sheets but it influences them as an energy efficiency component (it lowers the ratio of energy consumption per unit of GDP). The growth in the contribution of decentralized energy production also contributes, albeit moderately, to the recent dampening the growth in national demand for electricity [39]. In 2018, decentralized solar energy production allows peak clipping by nearly
800 MW (more than 12.6% of yearly maximum) and energy generation of about 1,500 GWh (more than 4% of injected electricity).

The National Energy Strategy (NES) \([40]\) provides that Morocco must have accumulated 3 million m\(^3\) of solar thermal collectors in 2030. However, it does not seem that the current pace allows reaching such a goal. It is not evident that the NES has clear objectives for PV systems connected to the LV and MV grids given the number of contradictory figures circulating in the official documents and presentations. However, some presentations provide that Morocco should reach 449 MWp of PV connected to the LV and MV grid, which should be already there, but without any incentive policy. Small-scale projects (like distributed photovoltaic and domestic solar water heating), offer an interesting potential for job creation (25 jobs per installed MWp in PV and 0.7 jobs per installed thousand m\(^3\) in solar thermal) and improve energy intensity while reducing energy dependency: signs of progress are still necessary to unlock the potential of this decentralized energy.

Since 2011, the private PV market has become flourishing in Morocco. It reaches nearly 70\% of annual sales of 280 MWp and 75\% of total sales of 718 MWp by the end of 2018, this, well before the adoption of the Decree of the electricity injection application on the low voltage network. Indeed, we must know that the Law 58/2015 came to allow the injection of electricity on the grid Low Voltage Law 13/2009 that tacitly prohibited. The competitiveness of solar PV against distributors’ electricity prices (reaching 1.80 Dhs / kWh in the Low Voltage grid and 1.20 in the Medium Voltage grid) will accelerate the PV penetration rates in Morocco. At the same time, many technical devices increasingly facilitate the consumption without having to inject electricity out of the meter or to allow distributors to detect solar PV installations invisible from the outside. Indeed, almost all of Morocco’s low voltage electrical counters rotate in opposite directions when the electricity goes into the grid, distributors are now hunting these situations to install non-return counters. Thus, what was inevitable \([41]\) is happening and it is becoming increasingly urgent to adopt, by Decree, the net-metering approach and its implementation modalities to encourage subscribers to declare their solar PV installations to control the quality of the inverters. It is essential that "synchronous" inverters used for injection to be of sufficient quality to avoid harmonics in the power grid, otherwise, they could undermine some equipment in the neighborhood and, presently, there is no way to protect against this. The "net-metering" approach will create a shortfall for electrical distributors and, they say, will call into question the equalized low-voltage electricity tariff system.

Despite a very low contribution to public procurement and tough competition heating by butane gas, the solar thermal market follows a regular and stable growth, albeit insufficiently fast for heat energy from solar take substantial shares in consumption Moroccan energy. It would be useful to adopt, by decree, removal of the subsidy on butane gas with a simultaneous redeployment of funds allocated to subsidies by the "Caisse de Compensation" to targeted social assistance for the two-fifths of the least favored population. This would have multiple positive effects:

- Performs a redistribution of wealth by strengthening the social character of the state while helping to expand the banking rate of the country,
- Reduces Morocco's energy dependence index:
  - Limiting the waste of too cheap butane gas,
  - Lowering butane gas expenses for heating domestic water,
- Discouraging the use of butane gas pumping for agricultural irrigation
  - Encourages solar thermal installations.

If this has not been done, it is probably because the successive governments of Morocco feared violent street protests, which might focus on raising the price of butane gas ignoring the financial counterparts. There, the pedagogy of political communication surely has a big role to play.

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