Direct DC use of PV for cooking and sanitary

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Abstract. The energy from solar can easily be harnessed to be used for various applications and grid injection. For cooking, different techniques can be utilized. Some people use the sun to cook. Other people use batteries and inverters even at noon. Hence, the cooking system becomes expensive. In fact, Photovoltaic panels did not decrease considerably in price. This paper proposes a simple electronic circuit that a Photovoltaic system can directly be used for cooking. The circuit aims at facilitating a cooking plate user to set a duty ratio. The duty ratio is limited to maintain the array voltage above a minimal level to avoid that it operates too far away from the maximal power point when less power is available. Moreover, it shows to be cost-effective compared to Photovoltaic grid connected and to charcoal.

Key words— PV, dc power supply, cooking, sanitary.

I. INTRODUCTION

The World experiences the climate change effects. This takes its origin from the carbon emission from fossil sources. The developed countries traditionally avoided fossil sources for cooking. For the developing countries, 80% of people still rely on cooking using wood or charcoals [2], [6]. Different scholars have shown that they are significant health problems for people who use daily wood and charcoals for cooking and heating needs. The charcoal and wood traffic involves some transportation, which increase the cost and CO₂ emission. People may get cancer, pneumonia, heart and lung diseases because of the traditional way of cooking [2]. Researchers have shown as well that wood cooking based diminishes local air quality through toxic smoke emissions like black carbon. Using wood for cooking also contributes to deforestation. Solar Atlas has found out that a household in Africa uses 2737 kg of wood per year [4]. This is equivalent to 4024.125 kg of CO₂ per year per household. Each year the CO₂ emission still increases. Fig.1 shows the projections of the CO₂ in 50 years worldwide [3], however, this tendency should be countered. The today background CO₂ increases 2.71 ppm/year [7]. At that rate the CO₂ gets 635 ppm in 2100. Such a constant slope is close to an emission/capita inverse proportional to the world population. For several reasons 600 ppm is already too much: climate change, ocean level, with some added CO₂ from heating, cooking or inside buildings starts the level of reduction of human cognitive ability health [5]. So a rather drastic reduction is needed to reduce it although the population might increase a lot. One way to reduce the increase of CO₂ emission is to integrate optimally the use of renewable energy in all countries. Some studies are even more pessimistic regarding population increase, with little renewable energy [Fig. 1].

FIG.1 C02 prediction [3]

Solar is among the leading renewable energy that is being exploited. Solar system can be a standalone or grid connected system. Mostly, a Photovoltaic (PV) system is converted to an AC power supply. This makes the PV system expensive. It was already quit common to use PV to pump water “as and when the sun shine”. Today, it is cheap enough to use it also for water heating. A PV system could have a positive impact on reducing CO2 emission, if people also use it for cooking. This paper intends to show how the PV system can be a direct use system for cooking using a simple electronic circuit connected to a cooking resistor, without batteries, so it is renewable and sustainable. By comparing with the AC grid, the paper proves that a direct use of PV system for cooking and sanitary is more cost effective than using PV system after being converted to AC power supply. It shows as well that the proposed system is more cost effective, safer and healthier compared to wood and charcoals.

II. COST OF A DIRECT DC PV COMPARED TO OTHER SOLUTIONS

DC grids get a renewed interest over the world in the electrical engineering field. The authors in [8,9,10] showed also that a local DC distribution system has higher efficiency compared to an AC distribution system. In general, DCDC converters are much cheaper than DC-AC.

The table 1 shows the cost of both direct use of a PV system and a grid connected PV system [1]. PV panels cost 380 Euros/ kW peak for private people. Low cost PV panels cost down to 200 Euros/ kW peak in large-scale application. For a grid connected PV system, more costs are added to have the total installation of the system. Mainly more costs are related to inverter, connection, grid installation, power plant installation and maintenance fees. Many people think that DC is automatically low voltage; however, Table 2 shows that it is better to use panels in series to reach higher voltage. Moreover, if a battery storage component is used in the PV system, the cost goes really high, as the lifetime of the battery is much lower than the PV panels. Table 1 shows the cost of two types of batteries: The cost of Li-ion type is 300 Euros/kWh whereas the cost of Pb-acid is half of the previous type.

TABLE 1 Cost of a direct DC PV compared to a grid connected system cost [1]

	Direct use of PV	AC grid	Battery Storage
Investment	Cost of only a PV panel is 380 €/kWp VAT included (from Private) 200 €/kWp VAT excluded from big farms	Connection costs Installation Power plant maintenance	Li-ion type 300 €/kWh, Pb-acid: 150 €/kWh
€/kWh	Over 25 years, without interest, at 1000 kWh/kWp/year 20% average degradation 1000 is Belgium, $385/(800*25)=0.019$ €/kWh Rwanda: 1.5 times lower cost Company $200/(800*25)=0.01$ €/kWh, but transport cost	If not subsidized and not abnormally taxed energy bill: Private: 0.1...0.3 €/kWh Companies: 0.06...0,15 €/kWh VAT excluded)	1500 equivalent full charges (EFC) Li-ion $300/1500=$ 0.2 €/kWh Pb-Acid 150/500: 0.3€/kWh

TABLE 2: Distance and power output at 10% drop in a 2.5mm² cable, used at 15A[1]

2.5mm² Cu wire, 10% voltage drop, $\Delta=20 \times 10^{-9} \Omega \text{m}$ 16 mΩ/m cable giving 0.24V/m drop at 15A			
DC Voltage [V]	Panels in series of each 60 Si-PV cells	Length [m]	Power out [W]
12		5	162
24		10	324
48		20	648
96		40	1296
120	4	50	1620
240	8	100	3240
(230 Vac)		95.8	3105
300	10	125	4050
350	12	145.8	4725
400		166.7	5400

It is obvious that once a direct DC PV system is used for cooking during day, the cost per kWh for cooking is tremendously reduced. For a PV system with batteries, the battery cost of ownerships adds 0.2 to 0.3 €/kWh. For the PV panels only, used in direct DC, 1 kWh will cost 0.019 Euros. This means if the remaining energy is used for sanitary or for water heater, a direct DC PV use costs over its life 10-15 times less compared to a battery type of PV system. Even if some oversizing of PV panels would be needed, it still makes sense. Replacing batteries also corresponds to a considerable material use and CO₂ emissions. The benefit of a direct DC PV use is not only realized at a level of bill of materials but also it is observed at the level of losses. Table 2 shows the DC losses in wires. From the table is obvious that the direct DC PV system use has fewer losses in cables as they are much shorter than a distribution grid. In the specific case of Rwanda, cooking is often done using charcoal. This is an expense of about 20

€/month for a household and tends to increase deforestation. It is also not healthy for the people around it especially for women and children. Suppressing cooking as an emission of CO₂ could be a serious change in CO₂ footprint for developing countries, or at least a better compromise with deforestation and competition with agricultural surface. One has to take in account that e.g. Rwanda has a higher population density than e.g. the Netherlands.

The idea is that several appliances work together on PV panels. An electric hot water boiler is used to collect what is not used for other appliances [1]. This stabilizes the voltage to for example 180Vdc for 6 panels, at 30V MPP/panel in series if the maximum temperature is not reached, and it can be 36V/panel if it is not loaded. Cooking should have priority on boilers, but needs also be regulated (limited) by hand. The traditional ON/OFF temperature thermostat in a cooking plate is not suitable to regulate the plate. For example, the PV might deliver 360 watts to a cooking plate of 40 Ω . The on-state would result in 193 W. Also the thermostat in pure DC will arc and be destroyed at turn off, only the plug seem to accept DC. However, with a PWM control and hence regulate the voltage at some 175V, it can be kept much closer to the maximum power point MPP resulting in about 360W, which is a bit slower than the full power, but mostly enough, so it can also be used in cloudy weather and without a solar tracker. At full sun, the cooking plate can be controlled by hand to limit the power and the remainder goes to the boilers. Hot water of 70°C is sufficient for instant coffee, or to cook rice faster. In this article, the research concentrates on the cooking circuit. The aim is to get to a simple circuit that can be serviced in the third world with less knowledge of (power) electronics without computer, and a long life expectancy. Fig.2 shows the proposed circuit that will allow the PV DC input to match to the cooking plate as a load. The circuit does not have a DC-DC converter as an internal power supply in order to reduce the cost and increase the reliability. The circuit has the ability to control the control the cooking plate in PWM. C1 is a DC link capacitor that links the PV to the circuit. It is the only electrolytic capacitor in the circuit. The IRS2153D, is originally a self-oscillating half-bridge gate driver Integrated Circuit (IC), in fact here, IRS2153D is hacked for a different use, but its features make it still cost effective and interesting.

Fig.2 A proposed circuit that can facilitate a direct DC use of PV for cooking and a boiler.

FIG.3 Voltage control for PV panel for one panel

The IRS2153D contains a Schmitt-trigger timer, a low side driver and also a high side driver, which is not used. It has other efficient features such as an internal 15.4 power supply Zener diode, an under voltage lockout a low current consumption and only 8 pins. If the voltage at the PV input is above 14.9 V (PV panels voltage high enough) the resistor divider at the base of Q2 will keep Q2 in the off state. In that case, the duty ratio can be controlled by the potentiometer R8.

If the chosen duty ratio by R8 is too high so that the panel voltage drops to a lower level, the transistor T1 will be conducting, so that the voltage across the R6 goes high. A higher input at the IRS2153 CT input results in a lower duty ratio. Hence, the MOSFET Q1, will be more off. Consequently, the cooking plate will take all the power available at that moment. R5 is used to set the point at which the PV voltage is controlled. R6 should be able to lower the maximum duty ratio set by R8. We know that some compromises are taken, such as not a constant frequency, but the system works well in practice. A typical resistance of the cooking plate is 40 Ohms. Although the cooking plates are designed for 230V, 180 V with a duty ratio which is about 90% maximum is sufficient for most cooking

$180^2/40 \times 0.9 = 729\text{W}$. At full sun, and not too hot panels, and if the electric boiler is not on, the voltage may rise up to 35V/ panel, 6 panels: $(35 \times 6)^2/40 \times 0.9 = 992\text{ W}$ is available. If cooking starts with water at 60°C (from the sink boiler), 2 liter of water needs in principle $2000 \times 40 \times 4.18 = 0.334\text{ kWh}$. even with 729 W it is attained in less than 30 minutes. To reduce the heat losses, a cover should be placed on the pot and above it a second larger cover. A bit

skilled persons can cook potatoes in 10 mm water with two covers. It goes fast as no superfluous is heated. It takes even less time than “normal”. All components that can be used for the circuit are shown in Fig.2. The resistors R7, R8, R11 and C3 determine the minimum frequency for the oscillator. In fact, the related minimum time constant is 2.2 ms . OFF time of about 1ms is certain to avoid arcing in contacts. The circuit is be powered by the resistor R2 from the PV system. As the frequency is very low, a minimal current of 1.8 mA is sufficient. Six panels of 30 V, 275W/ panel might be connected in series. The power of 1650 W peak will be available if the sun shines perpendicular to the panels. In Rwanda, one string can be sufficient, (in Belgium two strings are better, possibly 7 panels/string, to use it even in cloudy conditions. The Cooking plate characteristics have to match with the rating power of the direct DC use of the PV system. The system allows powering a boiler in case the voltage goes high in the range between 180 and 185 V, a similar but different circuit can be used for that. For normal cooking, the voltage ranges between 175 and 180 V. This more clear in Fig.2. Each panel voltage will contribute to work in the mentioned ranges. The control might be reliable because it does not host any microcontroller system. The next section gives the simulation, experimental work and discusses results.

III. SIMULATION AND EXPERIMENTAL RESULTS

The circuit was practically implemented. Fig.4 shows the experimental set up. The setup is composed of a power supply that has capability to emulate a solar panel. The electronic circuit board to interface the power supply to the cooking plate. A variable resistor replaces the cooking plate. The main purpose of the experiment is to verify the feasibility of the circuit in Fig.2. The verification compares the output power of the direct use PV system to the power range for a few different appliances (Table 3). The specific objectives of the experiment is to validate the features of the circuit, which are the capability of cooking with different power range, limiting and controlling the circuit output voltage. These features must be flexible with the characteristics of the PV panels. The PV emulator helped to evaluate the behavior of the direct use of PV system for cooking purpose. The results of the experiments are shown in Table 3 and 4 for different irradiance at load of 50 Ω and 34 Ω respectively. The output power of the system are very close to the output mentioned in Table 3. It shows that slow cooker and snack oven can be effortlessly supplied by the system.

TABLE 3 Cooking power range for a few different appliances [4]

Appliance	Watts (on label)	Watts
Slow cooker / crock	285	285
Snack oven	650	660
Frypan (230mm)	700	752
Hot plate	1100	1099
Electric jug	1400	----

TABLE 4 Direct PV system for cooking with a load of 50 Ω

Irradiance[%]	PV output Voltage[V]	Current[A]	Power [Watts]
25	180	1.2	180
50	174.1	2.65	460
75	184	2.76	510
100	194.8	2.76	560

TABLE 5: Direct PV systems for cooking with a load of $34\ \Omega$

Irradiance[%]	PV output		Power [Watts]
	Voltage[V]	Current[A]	
25	153.6	0.99	150
50	153.6	1.99	310
75	163.2	2.97	490
100	170	3.85	654.37

FIG.4 Direct DC use of PV system for cooking

Fig.5 Duty ratios of the PV direct use for cooking

FIG.6 cooking plate output voltage (yellow) and IRS2153D output voltage (purple)

Yet, this is not the only condition to be verified but also capability of controlling power and voltage must be proven that are efficiently working properly. To achieve to this, the circuit was tested at different duty ratios. Fig.4 a) shows that the duty ratio can go up to 86.7%. During this period, the cooking plate is subject to high power. Fig.4 b) shows that the system has capability to reduce the power and in some necessary case the power can be cut off (duty cycle is 0) once cooking process is at the end. The system is operating at lower power.

The voltage control allows the cooking plate to operate at 150 V dc and 700 W. It was approved that R5 and R8 implement voltage control following the variation of the maximum value of the voltage in Fig.2.

In practice, 6 panels can be enough but they can supply lower power of the appliance, yet some grids are not much better. To overcome this challenge, 7 panels in series can be used and this effect of lower power can disappear. The voltage is still acceptable as the duty ratio is not 1. The output voltage can be $(7 \times 36) \times 0.9 \times 0.5 = 239\text{V}$, which is within the tolerance of 230V. At 8 panels or more the maximal duty ratio should be limited. At 4 panels instead of 6 the system can be adapted to work, but the mismatch with 230V becomes high.

IV. CONCLUSIONS

Renewable energy sources have been exploited in order to avoid CO₂ emissions. Solar PV panels can be used on many places and in very different ways. Converting solar energy to ac system is the method that is mostly used. This paper proposes a pulsed DC direct use of PV system for cooking and what is not used can be “dumped” in hot water in a boiler. The proposed topology has shown a good performance in terms of regulating voltage close to the maximum power. A cooking plate was used as an example. The circuit is based on a low cost driver, the IRS2153D. Especially if combined with a hot water (sink) boiler, the system can be very cost effective, even if not all energy would be used, but gradually more appliances could get a “DC-ready” label. The reason is that batteries may be avoided for the main energy consuming appliances. All in all, the paper proved that a cooking plate user can set a duty ratio that the array voltage is maintained above a minimal level to avoid that it operates too far away from the maximal power point when less power is available.

REFERENCES

- [1] A. Van den Bossche, “Direct use of PV panels,” ISR- 26 to 29 March ,Conference-Egypt, key note.
- [2] Samantha Nhi Huynh, “solar cooking in namibiaAssessing the performance of a parabolic solar cooker,” 2014, Lund.
- [3] <http://euanmearns.com/global-co2-emissions-forecast-to-2100/>
- [4] <https://www.daftlogic.com/information-appliance-power-consumption.htm> [5] Global Alliance For Clean Cookstoves: <http://cleancookstoves.org/>.
- [6] IPCC: Climate Change 2014: Synthesis Report (2014): <http://www.ipcc.ch/report/ar5/syr/>
- [7] <https://www.theguardian.com/environment/2019/jan/25/worrying-rise-in-global-co2-forecast-for-2019>
- [8] H. Pang, E. Lo, B. Pong, “Dc Electrical Distribution Systems in Buildings,” International Conference on Power Electronics Systems, Nov. 2006, page(s): 115-119.
- [9] J. Ciezki, R. Ashton, “Selection and Stability Issues Associated with a Navy Shipboard DC Zonal Electric Distribution System,” *IEEE Transactions on Power Delivery*, vol. 15, no. 2, Apr 2000, page(s): 665- 669
- [10] K. Engelen, E. Shun, P. Vermeyen, I. Pardon, R. D’hulst, J Driesen, R. Belmans, “The Feasibility of Small-Scale Residential DC Distribution Systems,” IEEE Industrial Electronics Conference, Nov 2006, page(s): 2618-2632.