# Direct Drive Photovoltaic Milk Chilling: Two Years of Field Experience in Kenya

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**Abstract**

Direct drive solar milk chillers have been successfully developed and demonstrated with two and a half years field of operational experience in the Nakuru milk shed of Kenya. These innovative solar farm milk chillers (FMCs) are the first such units ever to be deployed and have been successfully operating with no issues or failures. The FMCs enable dairy farmers to boost incomes by selling chilled evening milk which would otherwise not be sold to dairy processors the next morning due to overnight spoilage. Milk is a highly nutritious, but perishable food, the storage quality of which cannot be improved once it has left the farm; thus, it is imperative to chill milk to below 10˚C within 4 hours after milking at the point-of-production (on the farm) to protect quality. The solar FMC technology as been used to chill from about 25 to 40 liters of milk overnight to about 4°C. No overnight solar chilled milk was rejected by milk buyers in the 2-year study (traders and dairy cooperatives) and farmer incomes were significantly increased by over 30 percent.

*Keywords: photovoltaics, direct drive solar refrigeration, milk chilling, Kenya*

## 1. Introduction

SunDanzer Refrigeration, Inc. (SDZR) and Winrock International (WI) have partnered to develop and deploy the world's first solar farm milk chillers (FMCs) to help East African dairy farmers sell their evening milk to dairy processors that otherwise would spoil or forced consumed. The ***Photovoltaics for Sustainable Milk for Africa through Refrigeration Technology (PV-SMART)*** project aims to tackle off-grid milk cooling under the United States Agency for International Development (USAID) Powering Agriculture Energy Grand Challenge Program (PAEGC). PV-SMART began in 2013 to develop the world's first on-farm solar milk chiller. The SDZR/WI team is working in collaboration withthe County Governments of Baringo, the Department of Dairy and Food Science and Technology at Egerton University, and with dairy cooperatives and LLCs in Mogotio and Ngorika, and with the Happy Cow dairy processor in Nakuru. Chloride-Exide is the local firm representing SDZR and installing the FMCs.

Direct drive PV refrigerators were developed nearly 20 years ago and are commonly used for vaccine refrigerators for remote clinics (Foster, 2001). This project has scaled up this concept to develop an affordable direct drive with thermal ice storage capable of chilling up to about 40 liters of evening milk. The project has piloted 80 of these innovative milk chillers in Kenya and two units in Rwanda with UNIDO, allowing farmers to sell between 5 to 40 extra liters per day of higher quality evening milk. This results in additional farmer income, ranging from US$60 to US$500 extra incomes per month, depending on the number of cows per farm. Solar equipment investment payback averages about 6 to 12 months for these smallholder farmers based on increased evening milk sales.

There are over 850,000 smallholder dairy farmers in Kenya, about 85 percent of who do not have access to the national electric power grid. Diesel fuel is expensive and logistics difficult to deliver to small rural dairy farmers and uneconomical to use for small scale refrigeration. Thus, there has not been an economical method available for on-farm milk chilling for the vast majority smallholder dairy farmers in Kenya and other less developed regions globally. The typical Kenyan dairy farmer has about 3 to 5 cows, producing an average of about 8 liters per day of milk per cow (typically ~60% as morning milk and ~40% as evening milk). Dairy cooperatives have an


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organized morning milk collection system, but normally do not accept evening milk since by morning due to high bacteriological counts growing overnight. Due to the lack of on-farm refrigeration, evening milk is either forced consumed, sold cheaply to nearby neighbors or hawkers, or spoils. Only about 40% of milk produced nationally is processed in Kenya.

**Fig.1: Dairy farmer training for solar farm milk chillers (FMCs) in Ngorika, Kenya.**

This failing in upstream milk production causes milk spoilage and lost farm earnings. It also causes poor quality milk and further losses in earnings along the downstream dairy value chain. Of the milk that does arrive, much of it still has a high bacterial count due to lack of refrigeration, resulting in poor quality dairy products. Farmers could receive a premium price for better quality, refrigerated milk; dairy processors could charge a premium for better quality products if milk can be kept cool all the way from cow to consumer; especially during the all-important first four hours after milking that determine quality.

In order to enhance the value of milk from remote producers, *PV-SMART* has developed an affordable solar powered farm milk chiller (FMC) so these producers can deliver cool milk rather than warm to the central collection stations. The farmers also use FMCs on the farm to preserve other produce such as eggs, meat, fruits and vegetables. Besides demonstrating the technology proof of concept, *PV-SMART* is also working with stakeholders like Kenyan SACCOs (Savings and Credit Cooperative Associations) to provide financing for solar technologies like FMCs that can increase on-farm productivity and incomes. Farmers often need access to technology and credit on reasonable terms to finance the initial purchase of solar power systems, which have higher capital costs but lower operating costs when compared to traditional remote generation energy technologies like diesel gen-sets.

*PV-SMART* has a four-phase implementation strategy for developing, disseminating, and financing FMCs in Kenya:

- Year 1—Technology Development: Designed and tested prototype solar farm milk chiller (FMC) by scaling up an off-the shelf photovoltaic refrigerator (PVR) model. Surveys were conducted of smallholder dairy farmer’s needs, and besides milk chilling, a wire basket was added for perishable household food items, as well as two 5V USB ports for daytime cell phone, radio, and LED lantern charging.

- Year 2—Pilot Phase 1: Piloted the world's first solar FMCs to 39 smallholder dairy farms in Baringo and Nyandarua Counties of Kenya. A baseline control unit was also installed at the Egerton University (EU) Department of Dairy and Food Science for more in-depth testing and milk quality evaluations. Field evaluations and farmer surveys were conducted by EU.

- Year 3— Field Testing Pilot Phase 2: Based on Phase 1 field experience, design and testing of a next generation prototype was developed with 40 units deployed to Kenya and 2 in Rwanda with UNIDO: (i) design adaptations notably moving from a ground to roof mounted PV system; (ii) established a local dealer network with Chloride-Exide; and (iii) begin financing units to farmer with Kenyan Savings and Credit Cooperative Associations (SACCOs), starting with Skyline SACCO in Mogotio. Demonstrations are also expanding to new regions with Mercy Corps and GiZ, including for camel milk chilling.

- Year 4— Commercial Rollout Phase 3: Planning is underway to expand the solar FMC technology commercially in Kenya with Chloride-Exide. Encourage more SACCOS to finance FMCs to more dairy farmers throughout Kenya. Expand FMCs to Rwanda and Tanzania.

## 2. Direct Drive Photovoltaic Refrigeration

The SunDanzer solar FMC is a direct drive refrigeration unit with no batteries that uses thermal phase change material (ice) energy storage. The technology was originally developed in support of NASA's future planetary mission's refrigeration requirements 20 years ago (Ewert, 2002), and later commercialized for vaccine battery free refrigeration. This is accomplished by integrating water as a phase-change material into a well-insulated refrigerator cabinet and by developing a microprocessor-based control system that allows direct connection of a PV panel to a fixed or variable speed dc compressor. By storing ice in the walls of the refrigerator, it eliminates the needs for electro-chemical energy storage. The solar refrigerator uses a vapor compression cooling cycle with an integral thermal storage liner, PV modules, and a controller. The Kenyan solar FMC employs a fixed speed dc compressor. By storing ice in the walls of the refrigerator, it eliminates the needs of battery storage; ice never wears out and provides sufficient energy storage to cool 40L of milk overnight.

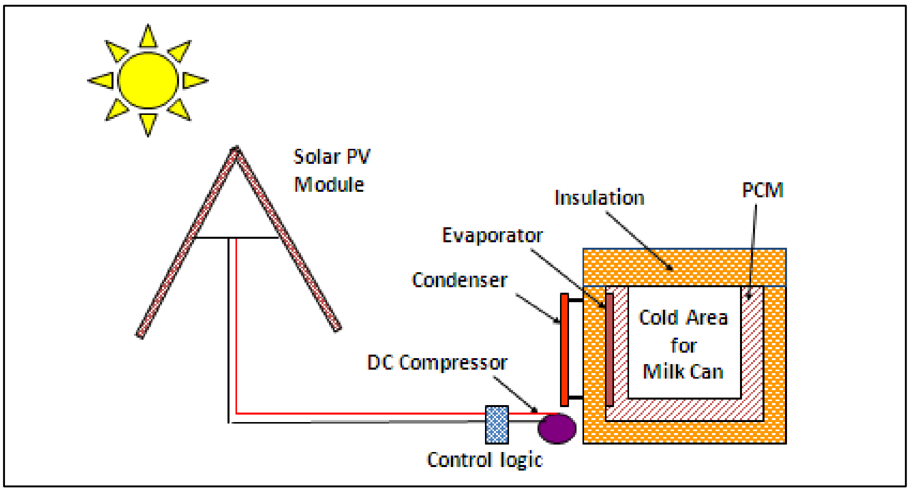


**Fig. 2: Solar direct drive refrigerator with DC compressor and E-W "fixed tracking" array (Foster, 2015).**

In addition to increasing the quality of product for farmers, the solar FMC has two 5 V USB plug ports capable of charging cell phones, radios, and solar lanterns which farmers use for themselves or rent out. Likewise, there are dietary and health benefits for farmer families to store vegetables, fruits, meat, etc. in the solar FMCs, which also reduces the frequency of trips to town to purchase fresh produce.


**Fig. 2: PV Powered Chiller Using Thermal Ice Storage and Brine Bags to Chill Evening Milk**

**Figure 1. Rooftop PV Installation for Mogotio Dairy Farmer FMC**

## 2.1. "Fixed Tracking" Array

The solar FMC system also uses an innovative East-West "fixed tracking" array to maximize compressor run time and not daily energy production. Conventional tracking increases both capital and operating costs due to additional hardware and maintenance requirements for moving parts. While a conventional equatorial facing PV array power output is well over the required power requirements for the FMC at solar noon; the East-West array's output wattage supplies the required compressor power for a longer period. Thus, increasing compressor run time providing longer operating hours for farmers to chill more milk. While this approach does not maximize energy usage, it does maximize ice production over the course of the day. PV prices have come down sufficiently that fixed tracking is a viable economic option over tracking without the future maintenance concerns. This type of approach works especially well in equatorial latitudes like Kenya. This simple approach provides reliable performance [4].

**Fig. 5. FMC PV array (510 Wp) with unique East-West fixed tracking array under test at Egerton University Dairy Science Unit.**

With the compressor running most of the daylight hours due to the E-W “fixed tracking” array (the array is not actually moving like a conventional tracker, but is fixed with half the array facing East and the other half facing West to maximize daily compressor run time). Ice is formed and stored into the walls of the PVR. Thus, there is no need for expensive battery storage and replacements. Ice does not wear out. Testing at New Mexico State University for NASA and SDZR on an early prototype PVR with ice storage was successful [2] and led to the development of direct drive vaccine PVRs using ice storage. The proven PVR technology was then increased in size for larger scale milk chilling.

In order to maximize heat transfer, the solar FMC incorporates brine bags, which do not freeze at 0°C, that are placed around the milk cans to increase heat transfer and cool milk quickly. Milk naturally contains antibacterial agents to protect the suckling young from potential infectious diseases; these antibacterial agents also slow bacteriological growth – the cause of milk souring. This effective natural protection is called the lactoperoxidase system, and has both bacteriostatic and bactericidal effects against some milk spoilage microflora for about the first four hours after milking. Bacteriological growth is further retarded when milk temperatures fall below 10°C and is essentially halted at 4°C. The FMC chills 25 liters of milk down to 10°C in a couple of hours, and the milk temperature by morning is about 4°C [4].

Since dairy farmers typically milk cows twice a day, once in the morning (~60%) and again in the evening (~40%), evening milk must be consumed or sold to neighbors or hawkers at a cut price. Even so, much of the evening milk spoils overnight. About 60% of milk in Kenya is not processed mostly due to the lack of on-farm chilling options. Solar FMCs increase farmer incomes from selling milk that would otherwise spoil, and some innovative dairy processors making cheese and yoghurt who need better quality product offer a Quality Milk Payment system incentive to dairy farmers. Solar chilling provides farmers the means to improve their milk quality and overall sales.

**Fig. 6: Kenyan dairy farmer with her solar farm milk chiller (FMC), which has become a prized possession in her home.**

## 3. Operational Findings

WI in collaboration with Egerton University Dairy and Food Sciences Department has been monitoring and evaluating (M&E) the performance and benefits of the Solar FMCs installed on the Mogotio and Ngorika Cooperative dairy farms. *PV-SMART* team is also monitoring solar irradiance at Ngorika and Egerton University sites. A few selected milk cans have a Hobo data logger installed on them to monitor milk can temperature data. The temperature probe is installed on the can with foam over it so that it measures true milk can temperature only.

The findings are based on milk can temperature data collected, co-op milk sales, surveys with the end-users, milk can temperature data, and field observations by the WI and Egerton University team. All of the original 40 piloted solar FMCs have functioned for 2.5 years with no failures, and no failures in the next 40 Phase 2 units as well. There was one Phase 1 unit which had a refrigerant leak upon delivery due to springing a refrigerant leak over some extremely rough roads traversed for delivery; this was easily repaired by a local refrigeration technician from Chloride-Exide for US$40 and the unit has functioned with no issues ever since. The solar FMC technology couples mature PV technology with mature vapor-compression technology and is very reliable.

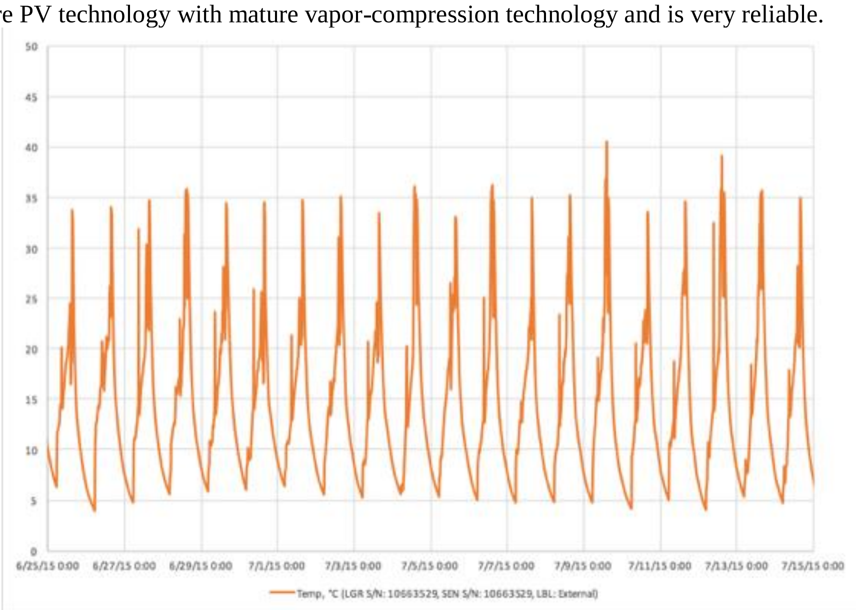


**Fig. 7: Example Daily Milk Can Temperature Cycles (daytime high when can is drying in the sun and nightimg low with milk).**

**Milk temperature**: The FMCs work well to chill 25 liters of evening milk to $4^{O}$C and lower. If some milk is not removed the next morning and left throughout the day, small quantities of milk can freeze, indicating the prototype FMC may have 'spare' cooling capacity for Kenya. The figure below shows daily milk cooling cycle for one of the farmers, milk temperature is repeatedly cooled to about 5°C. Note that the farmer puts the milk can outside in the direct sunlight for drying after cleaning so the can heats up to above ambient peak temperatures during the daytime.

## 4. Impacts and Results

PV-SMART is piloting 80 solar FMCs in Baringo, Kisumu, Nakuru, Nyandarua, and Wajir counties, as well as one control unit at Egerton University. The first 40 Phase 1 Pilot solar FMCs have operated flawlessly in the Nakuru milkshed of Kenya with no equipment failures in the first 2.5 years. The second Phase Unit are being installed from August – November, 2017.

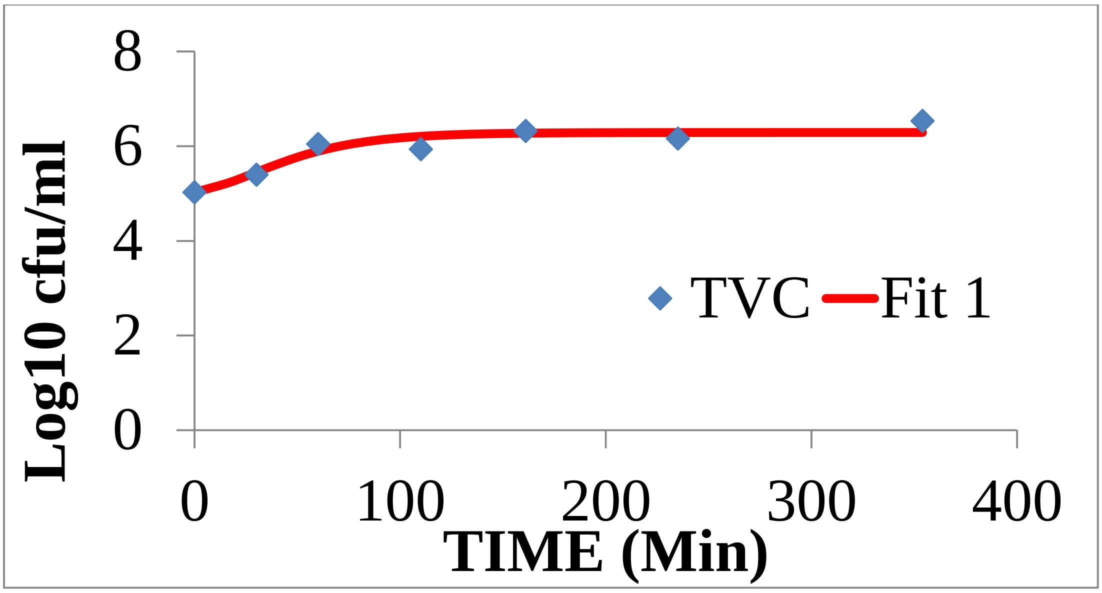


**Fig. 8: Total Viable Count (TVD) of Bacteria shows that once the milk is introduced to the solar milk chiller, bacteria growth is halted.**

The average dairy farmer chilled about 25 L of evening milk to 4°C; a few farmers chill as much as 40 L every night. Milk quality is maintained after milking and there have been zero rejections of solar chilled milk for any of the participating dairy farmers using solar FMCs, unlike from before. An informal farmer-to-farmer milk supply network was also organically created by solar FMC owners with excess capacity provided to their neighbors through FMC sharing (rent, barter, or purchase).

Over 92 percent of Mogotio farmers (lower elevation and hotter climate) and 67 percent of Ngorika farmers (higher elevation and cooler climate) reported increased milk sales directly attributable to chilling evening milk using solar FMCs. Other on-farm production factors include a severe drought in 2017 reducing forage and milk production for some farmers.

FMC field evaluations were conducted by WI in collaboration with the Department of Dairy and Food Science and Technology at Egerton University for units installed at the Mogotio Farmers' Cooperative Society Ltd. and New Ngorika Milk Producers Ltd. The farmer companies collect, bulk and deliver milk to two processors in Nakuru: Happy Cow Ltd and New Kenya Cooperative Creameries Ltd. Both are piloting quality-based milk quality payment (QBMP) schemes to incentivize farmers to improve milk quality. Based on solar FMC experience to date the key findings are below and summarized in Tables 1, 2, and 3.

- All 40 Phase 1 FMCs performed well and according to design, i.e. chilled 25 kg of warm evening milk to $<10^{O}$C within two hours, and to $<4^{O}$C by next morning collection.

- Some farmers were chilling up to 40 kg milk in plastic barrels to <$10^{O}$C prior by next morning collection – indicating potential to chill more than the designed 25 kg milk (ambient conditions vary).
- Some milk collector-transporter-farmers use the FMC to aggregate and chill up to 40 kg evening milk from 3 to 5 nearby farmers, charging additional KES 2 (~2 US cents) per kg.
- After homestead use of evening milk (for home and calves), the Phase 1 users are selling between 2 and 45 kg 'extra' milk daily – indicating gross incremental income gains ranging from KES 1,800 to 40,500 (US$18 to 400) per month based on an average farmgate milk price of KES 30/kg. Cows produce milk in the evening regardless of whether there is a market or not.
- Two head of household ladies earn 'extra' income from FMCs charging neighbour's cellphones - ~KES10 per charge x 10 = KES100 (US$1) per day.
- The FMC kept milk fresh until morning with zero rejections reported in two years.

**Table 1: Evening Milk Sales Increased Dramatically to Dairy Processors**

| Location | Did Milk Sales increase? | Evening Milk Usage and Sales | | | |
|---|---|---|---|---|---|
| | | Before FMC Installation | | AfterFMC Installation | |
| | | Home Consumption | Local sales | Home consumption /local sales | Sales to Dairy Processors |
| Mogotio n=19 | No (7.7% | 69% | 31% | 8% | 92% |
| | Yes (92.3%) | | | | |
| Ngorika n=20 | No (16.7%) | 27% | 73% | | 100% |
| | Yes (66.7% | | | | |

**Table 2: Comparison of milk stored in the Solar FMC**

| Parameter | Farm 1 | | Farm 2 | | Bench Sample | |
|---|---|---|---|---|---|---|
| | Evening | Morning | Evening | Morning | Evening | Morning |
| Room Temperature °C | 19.0 | 17.4 | 20.6 | 19.1 | 19.1 | 18.1 |
| Milk Temperature °C | 29.6 | 3.5 | 28.4 | 0.2 | 29.5 | 17.2 |
| Acidity (% Lactic acid) | 0.162 | 0.174 | 0.155 | 0.164 | 0.161 | 0.195 |
| pH | 6.64 | 6.59 | 6.59 | 6.57 | 6.64 | 6.24 |

**Table3: Milk quality change during overnight storage from Egerton University Dairy Lab**

| Parameter | Farm 1 | Farm 2 | Bench Sample |
|---|---|---|---|
| Time in storage (Hours) | 14.946 ± 0.168a | 15.361 ± 0.298a | 14.946 ± 0.168a |
| Titratable acidity (%LA) | 0.012 ± 0.012b | 0.009 ± 0.006b | 0.033 ± 0.022a |
| pH | -0.042 ± 0.170a | -0.021 ± 0.018a | -0.239 ± 0.167b |
| Log 10 CC | 0.808 ± 1.273b | 0.914 ± 0.865b | 3.373 ± 1.403a |
| Log 10 TVC | 1.023 ± 0.997b | 0.950 ± 0.587b | 3.946 ± 1.015a |
| Red figures indicate did not meet KEBS norms. | | | |

The key takeaway is that the solar FMC works and improves on-farm milk quality at point-of-production on the farm potentially enabling more quality milk to enter the dairy supply chain. The returns from investing in solar FMCs appear are under a year, even for smallholder dairy farmers. WI is working with the Skyline SACCO and other partners to finance solar FMCs in 2017 as there is a good business case with relatively low repayment default risk facilitated by the well embedded existing milk 'check-off' repayment system.

Thus, milk quantity and potential incremental gross earnings gain at current milk prices is excellent for these pilot units, with simple payback ranging anywhere from six months to one year depending on user milk production. From the initial surveys users sell between 5 and 45 liters of extra evening milk each day, indicating gross incremental income gains ranging from US$50 to $650 per month. Kenyan small scale financial credit institutions (SACCOs) have begun financing PVRs during Phase 2 of PV-SMART at an initial selling price of about US$1,850 per installed unit if roof mounted (pole mounting is more). The final commercial price may vary. Field surveys found that 83 percent of the Phase 1 pilot FMC farmers felt the solar FMC technology was worth the initial cost and is a worthwhile investment. Financing is key as over 70 percent of small holder farmers prefer a short-term (1 year) loan mechanism to purchase solar FMCs.

## 5. Conclusions

PV direct drive solar milk chillers (FMCs) have been successfully introduced and used in Kenya with zero failures in the first 2.5 years of operation. There is a significant increase in amount of milk sold and the farmer income accruing from the extra liters of milk sold. Smallholder dairy farmers have sold between 5 and 40 extra liters of evening milk each day, depending on their dairy herd size. The FMC kept milk fresh until morning with zero rejections reported from the milk collection center. Resulting farmer income gains ranged from US$60 to $500 per month, with expected FMC payback typically in less than a year. This type of solar milk chilling uses no batteries and has no regular maintenance requirements. There are over 5 million smallholder dairy farmers in East Africa who can benefit from this technology, not to mention the millions more of other off-grid smallholder dairy farmers in the rest of Africa, Asia, and Latin America that can also benefit from solar FMCs to improve livelihoods and delivered milk quality.

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